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VACUUM MELTING AND CASTING OF SUPERALLOYS

A REPORT

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

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This document is one of a series of reports dealing with the development of a class of high-temperature materials called superalloys. This development has been accelerated by the demand for better materials to meet the special needs and requirements in the aerospace field. NASA has been a major contributor to the overall effort.

The discussions in this report deal mainly with the latest techniques in processing superalloys, with emphasis specifically on vacuum melting and casting. NASA contributions to the technology are set forth, and equipment and techniques presently used in processing the metals are described. The information has been compiled by Battelle Memorial Institute-Columbus Laboratories. The document should be of value to investigators as a basis for further research in materials technology, and to manufacturers of equipment in which metals having high-temperature characteristics are required.

Ronald J. Philips, Director
Technology Utilization Office

Acknowledgements

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The discussions on vacuum casting contain significant amounts of data concerned with the so-called art of casting, much of which is proprietary. The authors are especially grateful, therefore, for the assistance given by several companies who were willing to discuss some of the sensitive areas in this technology:

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Muskegon, Michigan

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Wheeling, Illinois

TRW, Metals Division
Minerva, Ohio

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VACUUM MELTING AND CASTING OF SUPERALLOYS

CHAPTER 1. INTRODUCTION

NASA has had a multifaceted role in the development of vacuum metallurgy as a technology. Most obvious would be the requirements associated with the behavior of materials in the space environment and in the development of alloys, processing of materials, and physical and mechanical testing of refractory and reactive materials.

However, NASA's most important role in vacuum metallurgy as it is associated with superalloys has been: (1) the identification of application requirements for superalloys, (2) early and recent development of new and improved superalloys, and (3) the identification of controlled atmosphere processing requirements that were reflected in the improvement of superalloys for service.

The importance of NASA's role springs in no small manner from the early work in the vacuum metallurgy of nickel and cobalt-base alloys at NASA dating back to the immediate post-World War II period and early 1950's[1, 2] This early beginning and current and past involvements with superalloys sprang from and continues to be supported by the high-temperature material needs of jet engines[3]. Aerospace application requirements associated with space power systems[4, 5] and high-temperature structures have reinforced and amplified the importance of superalloys[6, 7]. Another facet of NASA's role in the vacuum metallurgy of superalloys is exploding on the technical scene. This is the production of prealloyed superalloy powders and the processing of the powders to fabricated parts for high-temperature use[8].

Therefore, NASA has had direct and indirect involvement in all of the facets of vacuum metallurgy. This involvement has been direct in research and development within its laboratories[9-11] and in the support of research and developments for materials[12]; indirect, in that NASA's requirements for aircraft and space spin off technology and create the facilities and experience in industry that encourage and make possible further developments and utilizations of this advanced technology for the solution of problems and industrial growth. The following sections detail the parts of this vacuum metallurgy technology associated with the melting and casting of superalloys.

CHAPTER 2. SUMMARY

The growth of interest in vacuum melting and casting is closely tied to the growth in use of nickel-base superalloys. Were it not for the demands of the superalloys for nonoxidizing atmospheres during melting and casting, better vacuum furnaces and production facilities would not have resulted. At the same time, the introduction of vacuum melting and the development of better casting methods have provided the stimulus for improved nickel-base and cobalt-base superalloys.

Of the factors influencing the growth of vacuum-melted superalloys, the aircraft gas-turbine engine has been the most important. Cast components were first used for the hot-nozzle guide vanes, solid or hollow; later cast superalloys became accepted as the solid rotating turbine buckets, and, as casting techniques improved, they were made into buckets with intricate cooling passages. An example of cast nozzles and wheels for the three stages of a small gas-turbine engine is shown in figure 1.

Because of the high aluminum and titanium content of the superalloys, it becomes necessary to vacuum-melt them to prevent gross pickup of oxygen and nitrogen and the formation of harmful films of nonmetallic materials. The wrought vacuum-melted superalloys, which at first were used mainly as rotating buckets on the aircraft gas-turbine engine, are now used as buckets (predominantly in the latest turbine stages) and as disks, structural forgings, fabricated sheet-metal parts, and rings. Some alloys that are called "wrought alloys" are being cast to shape because the overall cost is lower than that for forging and machining.

The two most important melting techniques currently used for the production of superalloy materials are vacuum induction melting and vacuum arc remelting. Vacuum induction melting offers excellent control over composition (including impurity content) while its major shortcoming is in the inferior properties of large castings produced from vacuum induction melts. Vacuum arc melting, on the other hand, provides significantly less control of composition during melting because the short time that the material exists in the liquid state is insufficient for melt sampling and subsequent additions to the melt, but the directional nature of solidification results in improved ingot properties. Because of the fundamental differences between these two melting techniques, vacuum induction and vacuum arc melting have, in general, not been competitors; rather, each technique has its own sphere of application. There has been an increasing tendency in recent years to use double vacuum melting, especially for the more highly alloyed superalloys. This technique consists of initial vacuum induction melting and casting to form an electrode for subsequent vacuum arc remelting. Double-vacuum-melted material essentially combines the advantages of the two vacuum-melting techniques, i.e., the close composition control characteristic of vacuum-induction-melted material as well as the improved ingot structures typical of vacuum-arc-melted material.

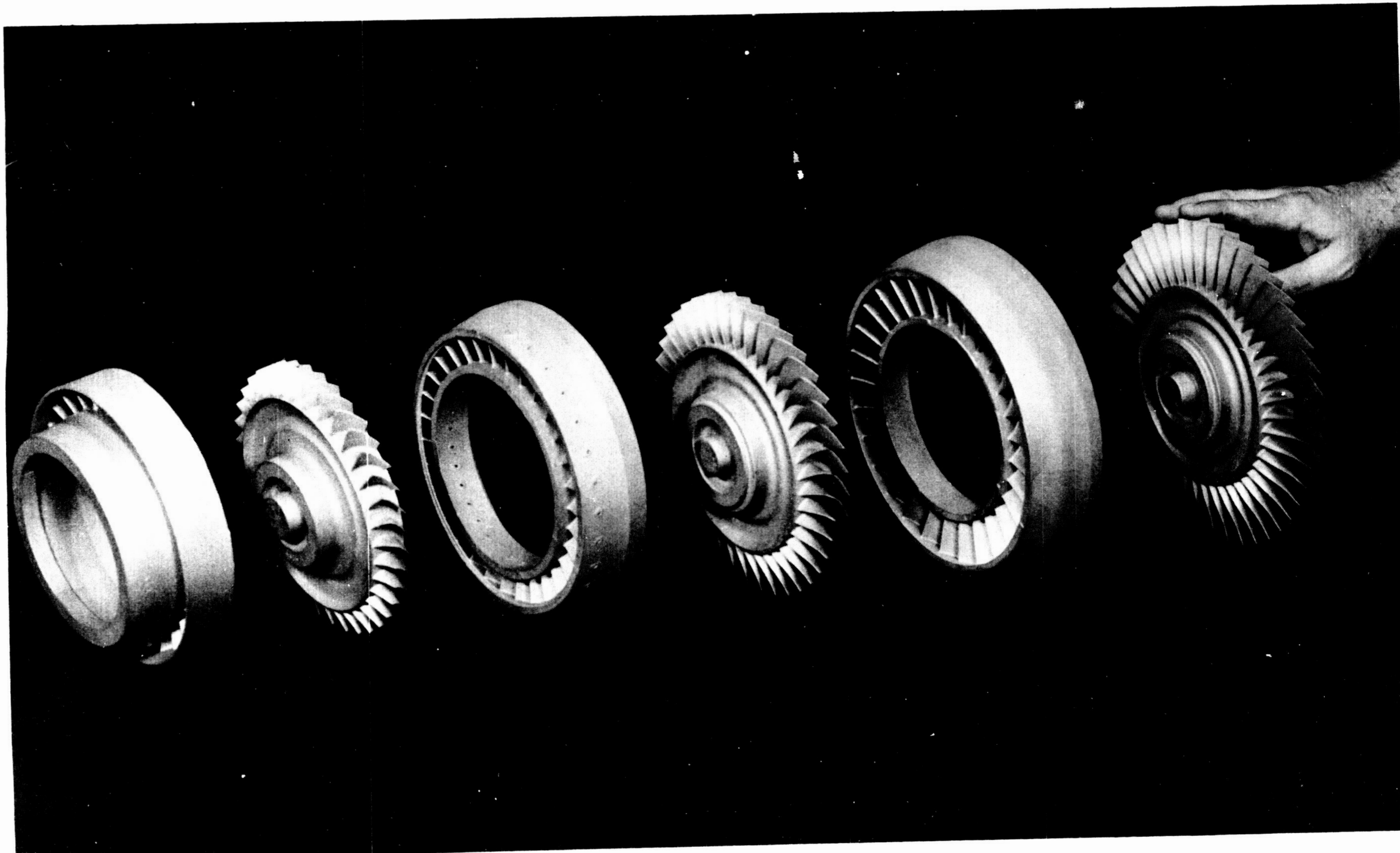


FIGURE 1. INVESTMENT-CAST NOZZLES AND WHEELS FOR THE THREE STAGES OF A SMALL GAS-TURBINE ENGINE

(Courtesy Misco Division, Howmet Corporation)

In recent years, interest in electroslag melting in the United States has significantly increased. The majority of the work conducted to date has been on steels, although some of the more recent studies have been concerned with the electroslag melting of superalloys. The results of these studies have, in general, been encouraging, and electroslag melting is now used as a commercial production technique for some materials. The principal advantage offered by this technique is the highly directional nature of solidification with accompanying increases in ingot fabricability and decreases in segregation, microporosity, and piping.

The fourth melting technique pertinent to the production of superalloy materials, which has never been used as a commercial technique for superalloys, has only recently been evaluated on a experimental basis for these materials. This technique is electron-beam melting. The principal advantage of electron-beam melting is the high purity which is attainable, while the traditional shortcomings of the process have been high cost and the removal of volatile alloying additions. Several developments in electron-beam technology, however, cause this technique to appear more attractive for the melting of superalloys. The first is the hearth melting furnace developed at Airco-Temescal. One advantage of this furnace is the high production rates possible with the potential for favorable economic competition with vacuum arc and vacuum induction melting. Another advantage is due to the continuous flow of molten metal along the hearth, since highly volatile alloying additions can be made downstream just prior to casting. Thus, the vaporization loss of these alloying additions is minimized.

The vaporization loss of volatile alloying elements can also be minimized by an alternative electron-beam process known as plasma electron-beam melting. These furnaces operate at higher pressures than do conventional electron-beam furnaces with the resultant decrease in vaporization losses of volatile constituents. For the same reasons, however, the purifying action is somewhat less for plasma electron-beam melting than for high-vacuum electron-beam melting; however, the plasma electron-beam-melting process produces cleaner material than either vacuum-arc- or vacuum-induction-melting processes.

The only commercially important casting process currently used for superalloy production is investment casting. Molds for these castings are prepared by investing (i.e., coating) a wax (or plastic) pattern with a refractory slurry. The pattern is then removed by melting and the refractory shell is fired to obtain a strong mold. The particular advantages which investment castings have over forged or welded assemblies include close dimensional control, fine surface finishes, the ability to cast intricate shapes and the ability for microstructural control (e.g., directional solidification). In addition, some alloys are not amenable to hot forging, and casting is the only practical fabrication technique.

CHAPTER 3. COMPOSITIONS, PROPERTIES, AND APPLICATIONS

Nickel-Base Superalloys

Table 1 gives the compositions of some commercial superalloys. The nickel-base superalloys represent, as a class, high-temperature alloys of superior strength. While the term "superalloys" is hard to define precisely because of the overlap with various other high-temperature alloys, one of the main characteristics of almost all nickel-base superalloys is that they contain aluminum and, with few exceptions, titanium. These constituents participate in the formation of gamma-prime (Ni_3 Al, Ti), the very powerful phase responsible for high-temperature strength. At the same time, titanium and aluminum have a strong chemical affinity for oxygen and nitrogen; therefore, if there is more than about 4 percent total of these elements in the alloy, it must be vacuum-melted to prevent the formation of harmful oxide films and nitrides.

We thus may have a good working definition of nickel-base superalloys:

> Nickel-base superalloys are those high-temperature alloys containing more than 50-percent nickel which must be vacuum-melted because of their high aluminum and titanium contents. (It should be mentioned that use of inert-gas atmospheres or electroslag melting might be possible alternatives, but they are not extensively used today.)

This definition excludes alloys that are primarily solid-solution or carbide-strengthened, such as Hastelloy Alloy X, Inconel Alloy 625, and IN 102. It also excludes certain of the earlier alloys that were once considered superalloys; Nimonic 80A, for example, the forerunner of the gamma-prime strengthened alloys, does not require vacuum melting. Also excluded are TD Nickel and TD Nickel-Chromium, which are strengthened by a dispersion of fine thoria particles. These alloys are powder metallurgically prepared and vacuum melting is not required.

Earlier definitions of superalloys centered around their high strength and oxidation resistance in the 1200 to 1900 F range. From a practical viewpoint, this meant those alloys that could serve as the rotating buckets in gas-turbine engines. Progressive widening of the definition sometimes led to the inclusion of highly oxidation-resistant alloys (Hastelloy X, for example) and alloys which have good strength in the 2000 to 2400 F range (TD nickel, for example), but these clearly could not serve as the rotating buckets of gas-turbine engines. Thus, insofar as nickel-base superalloys are concerned, the vacuum-melting criterion is compatible with the rotating-bucket criterion. An exception is Alloy 718, which lacks strength above 1200 F.

TABLE I. — COMPOSITIONS OF SELECTED VACUUM-MELTED NICKEL-BASE SUPERALLOYS[13-17]

Alloy	Nominal Composition (Balance Nickel), percent										
	C	Cr	Co	Mo	W	Cb	Ti	Al	B	Zr	Fe	Other[c]
					Wrought Alloys						
Astroloy	0.06	15	15	5.3	--	--	3.5	4.4	0.03	--	--	--
Inconel 700	0.12	15	28.5	3.7	--	--	2.2	3.0	--	--	0.7	--
Hastelloy R-235	0.15	15.5	2.5[a]	5.5	--	--	2.5	2.0	--	--	10	--
M-252	0.15	19	10	10	--	--	2.6	1.0	0.005	--	--	--
Nimonic 115[b]	0.1	15	15	3.5	--	--	4	5	--	--	--	--
René 41	0.09	19	11	10	--	--	3.1	1.5	0.01[a]	--	--	--
René 85	0.27	9	15	3.3	5.4	--	3.3	5.3	0.015	--	--	--
SEL-15	0.07	11	14.5	6.5	1.5	0.5	2.5	5.4	0.015	--	0.5[a]	--
Udimet 500	0.08	19	18	4	--	--	2.9	2.9	0.005	--	4[a]	--
Udimet 520	0.05	19	12	6	1	--	3.0	2.0	0.005	--	--	--
Udimet 700	0.10	15	18.5	5.2	--	--	3.5	4.3	0.05[a]	--	1.0[a]	--
Udimet 710	0.07	18	15	3	1.5	--	5	2.5	0.02	--	--	--
Unitemp AF1753	0.24	16	7.2	1.6	8.4	--	3.2	1.9	0.008	0.06	9.5	--
Waspaloy	0.07	19.5	13.5	4.3	--	--	3.0	1.4	0.006	0.09	2.0[a]	--
					Cast Alloys						
Alloy 713C	0.12	12.5	--	4.2	--	2.0	0.8	6.1	0.012	0.10	--	--
Alloy 713LC	0.05	12	--	4.5	--	2.0	0.6	5.9	0.01	0.10	--	--
B-1900	0.1	8	10	6	--	--	1.0	6.0	0.015	0.08	--	4.3 Ta
G. 64[b]	0.13	11	--	3	4	2.0	--	6.0	0.25	--	2[a]	--
G. 94[b]	0.06	9	10	4	4	4	--	6.0	Added	Added	--	--
GMR-235D	0.15	15.5	--	5	--	--	2.5	3.5	0.05	--	4.5	--
IN-100	0.18	10	15	3	--	--	4.7	5.5	0.014	0.06	--	1V
IN-738	0.17	16	8.5	1.8	2.6	0.9	3.4	3.4	0.01	0.1	--	1.8 Ta
M22[b]	0.13	5.7	--	2	11	--	--	6.3	--	0.60	--	3 Ta
MAR-M200	0.15	9	10	--	12.5	1.0	2.0	5.0	0.015	0.05	--	--
MAR-M211	0.15	9	10	2.5	5.5	2.7	2.0	5.0	0.015	0.05	--	--
MAR-M246	0.15	9	10	2.5	10	--	1.5	5.5	0.015	0.05	0.15	1.5 Ta
MAR-M421	0.15	15.5	10	1.8	3.5	1.8	1.8	4.3	0.015	0.05	1[a]	--
MAR-M432	0.15	15.5	20	--	3	2	4.3	2.8	0.015	0.05	--	--
Nicrotung	0.10	12	10	--	8	--	4.0	4.0	0.05	0.05	--	--
Nimocast 258[b]	0.22	10	20	5	--	--	3.7	4.8	--	--	2[a]	--
PDRL 162	0.12	10	--	4	2	1	1	6.5	0.02	0.1	0.5[a]	2 Ta
TAZ-8	0.13	6	--	4	4	2.5V	--	6.0	--	1.0	--	8 Ta
TAZ-8A	0.13	6	--	4	4	2.5	--	6.0	0.004	1.0	--	8 Ta
TAZ-8B	0.13	6	5	4	4	1.5	--	6.0	0.004	1.0	--	8 Ta
TRW 1900	0.11	10	10	--	9	1.5	1.0	6.0	0.03	0.10	--	--

(a) Maximum.
(b) British alloys.
(c) All alloys contain manganese and silicon, and most specifications contain maximum allowable amounts of these elements. Typically, the amount present would be 0.1 Mn and 0.2 Si, though considerable variation exists among elements.

Oxidation resistance, or more generally corrosion resistance, was once part of the criteria for superalloys. All the alloys contain chromium for imparting corrosion resistance, and the first of the family had about 20-percent chromium. As the strengthening alloying agents were added, the percentage of chromium was successively lowered, reaching as low as 5.7 percent in Alloy M22. Accordingly, oxidation resistance is often imparted by a diffusion coating, usually of the aluminide type. Oxidation resistance of the uncoated alloy should no longer be considered a criterion for superalloys; rather, the alloy and its coating must be considered as a system.

Figure 2 compares the approximate temperatures for rupture in 100 hours at 20,000 and 30,000 psi for various vacuum-melted superalloys. The cast alloys – including Udimet 500 and Udimet 700, which are normally wrought alloys – have higher creep-rupture strength than the wrought alloys. This is due mainly to their higher aluminum and titanium content of roughly 6 to 7 percent (wrought-alloy content is from 4.5 to 6 percent). Numerous exceptions make it difficult to generalize; nevertheless, it would be fair to say that workability decreases with increasing total aluminum-plus-titanium content. The workability of such high aluminum-plus-titanium alloys as Udimet 700 and Nimonic 115 seems to be increased by the presence of cobalt in their compositions(18). As a rule, when the aluminum-plus-titanium content exceeds about 6 percent, vacuum casting becomes the normal manufacturing method, and the alloys are called "cast alloys" rather than "wrought alloys".

Because these alloys are often used in rotating parts, they are compared in Figure 3 on the basis of operating temperature corrected for density differences.

Cobalt-Base Superalloys

Vacuum melting and casting of cobalt-base alloys was not practiced until recently. However, with the development of the "MAR-M" series of alloys based on strengthening by refractory metal carbides (particularly of tantalum), the use of vacuum became important. Alloys MAR-M 302 and 509 (see table 2) find their main application in the stationary nozzle guide vanes of gas-turbine engines, and are especially useful at higher temperatures but lower stresses than those for the rotating buckets. They show good oxidation resistance and good resistance to thermal fatigue. All of these alloys are vacuum-cast to shape.

Other recent cobalt alloy developments are AiResist 13 and AiResist 215(19), which are said to have high resistance to attack by

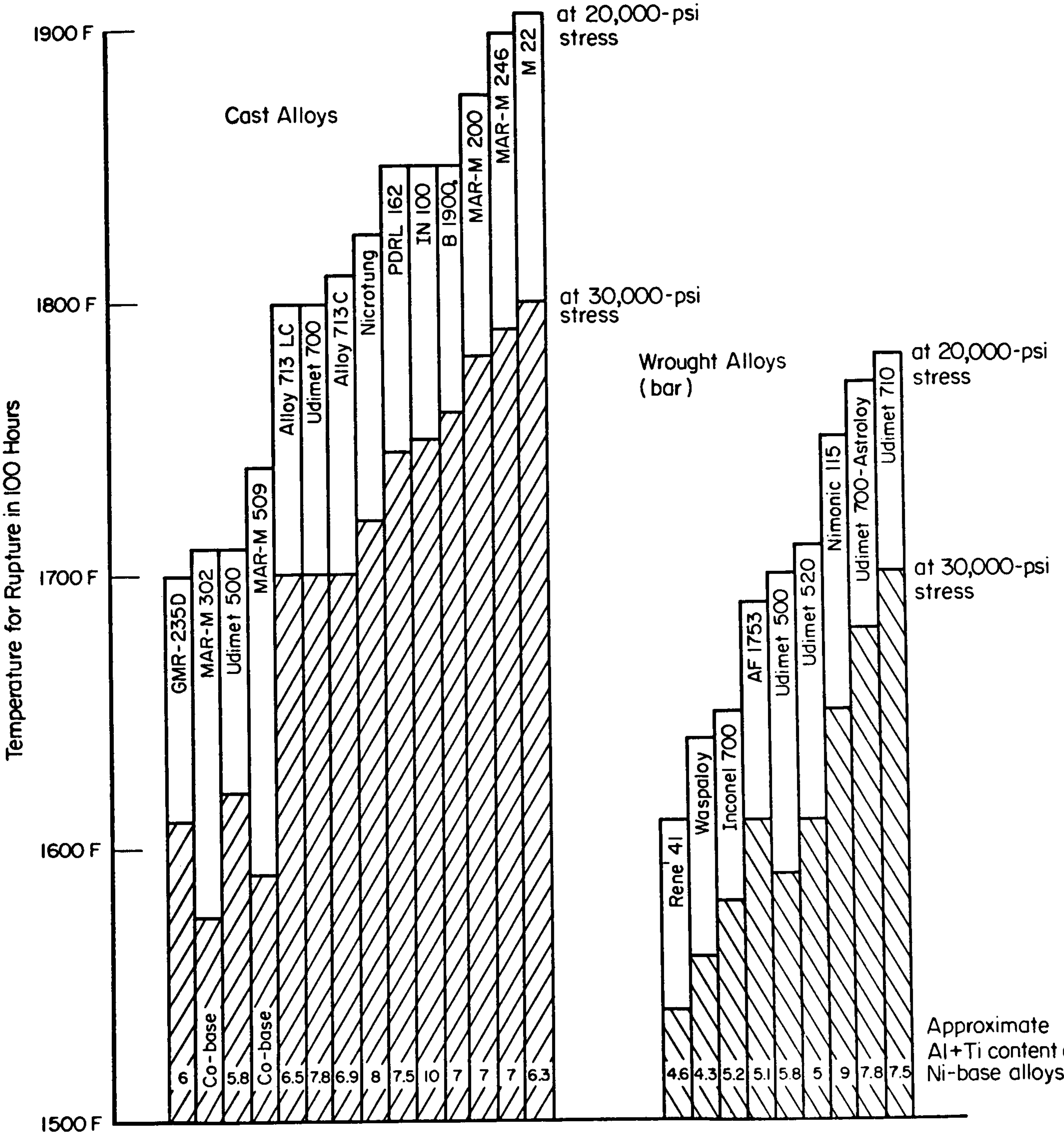


FIGURE 2. RELATIVE TEMPERATURE CAPABILITIES OF SOME VACUUM-MELTED SUPERALLOYS

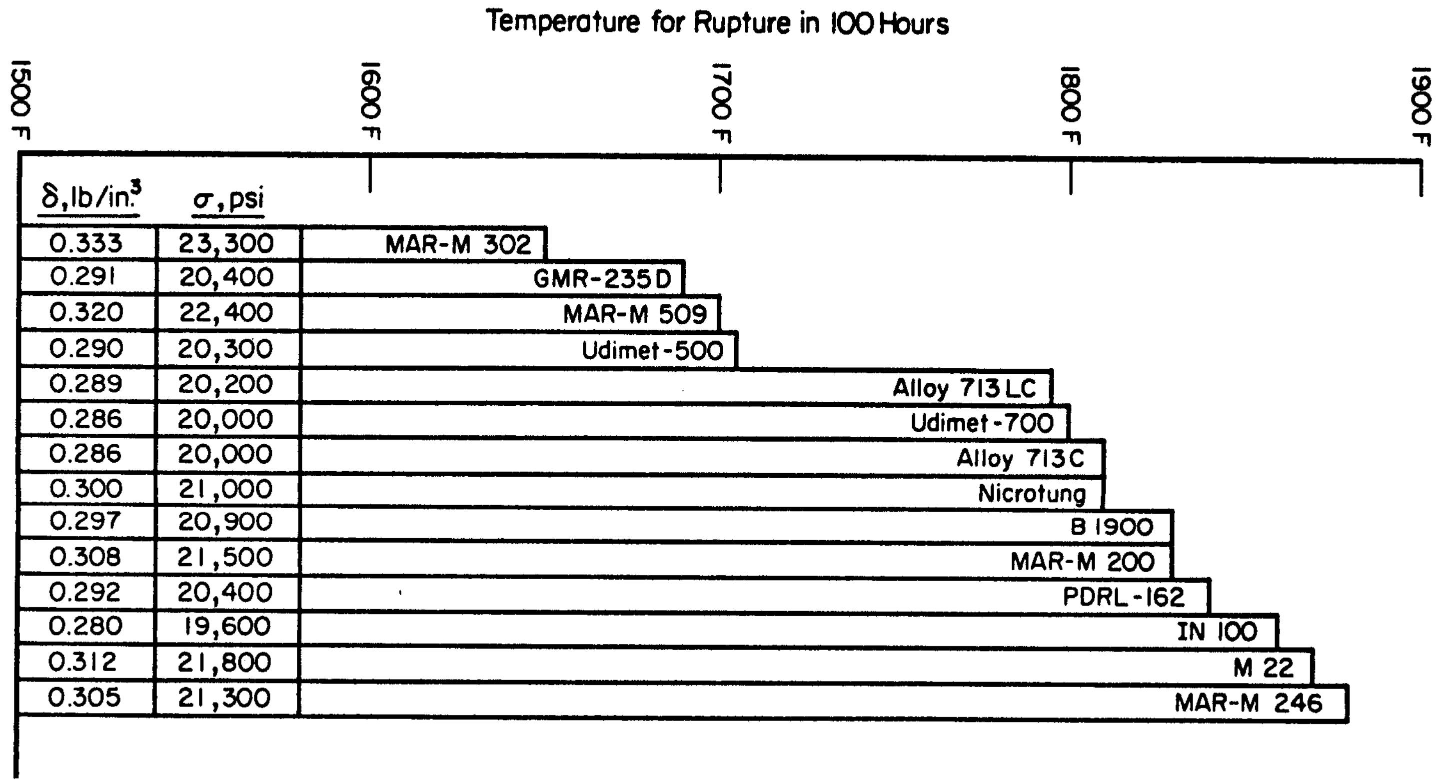


FIGURE 3. RELATIVE TEMPERATURE CAPABILITIES OF SOME CAST SUPERALLOYS ADJUSTED FOR DENSITY

All alloys at $\frac{\sigma}{\delta} = \frac{\text{stress}}{\text{density}} = 70,000 \frac{\text{psi}}{\text{lb/in.}}$

TABLE 2. — COMPOSITIONS OF SELECTED VACUUM-MELTED COBALT-BASE SUPERALLOYS[14, 19, 20]

Alloy	Nominal Composition[a] (Balance Cobalt), percent								
	C	Cr	Ni	W	Ta	Al	B	Zr	Y
				Cast Alloys					
AiResist 13	0.45	21	2.5[b]	11	2	3.4	--	--	0.1
AiResist 215	0.35	19	0.5[b]	4.5	7.5	4.3	--	0.12	0.13
MAR-M302	0.85	21.5	--	10	9	--	0.005	0.15	--
MAR-M509	0.60	23.5	10	7	3.5	0.2 Ti	0.01[a]	0.15	--
				Wrought Alloys					
AiResist 213	0.18	19	0.5[b]	4.7	6.5	3.5	--	0.15	0.1
MAR-M918	0.05	20	20	--	7.5	--	--	0.10	--

(a) Manganese and silicon are present in all alloys, typically 0.1 to 0.2 Mn and 0.1 to 0.2 Si.
(b) Maximum.

sulfur-containing atmospheres. These alloys gain their strength from refractory metal carbides, and their corrosion resistance from chromium, aluminum, and yttrium.

Two wrought cobalt-base alloys have recently been introduced which require vacuum melting: MAR-M 918 and AiResist 213. These alloys may find applications in heat exhangers, jet-engine combustion cans, tailpipes, and the like.

CHAPTER 4. FACTORS IMPORTANT IN MELTING AND CASTING

Physiochemical Considerations

The amount of gaseous impurities that remain within a vacuum casting is a function of a great many variables such as melt composition, crucible material, ultimate vacuum attainable, type of pump and pumping speed, trap temperature, time at temperature near the melting point, and the geometry of the melting furnace. Generalizations can be made, and some principles can be illustrated to indicate how clean-up of a gaseous impurity may be effected. For the most part this discussion is concerned with pressures ranging from 10^{-3} torr to 10^{-6} torr since it is within this range that most large melt furnaces operate.

Nature of residual gases in melting furnaces. - The sources of gas within a vacuum furnace are leaks from the atmosphere, virtual leaks through outgassing of walls and components, and back streaming from mechanical and diffusion pumps. The first source, of course, supplies mostly nitrogen and oxygen; the second supplies water vapor, hydrogen, and carbon monoxide (generally in that order); and the third source gives rise to heavy hydrocarbons that generally crack on contacting hot surfaces to form simpler molecules. A liquid-nitrogen trap can greatly reduce back streaming and trap the water vapor outgassing from the walls, but it has virtually no effect on carbon monoxide or hydrogen, or on any real leak of oxygen and nitrogen from the atmosphere.

Reaction of metals with residual gases. - A metal at elevated temperature in a reduced-pressure environment may be purified by vaporization of a volatile oxide. This can be caused by a reaction between a residual-gas component and an impurity in the metal (such as hydrogen with carbon to form methane) or, under some conditions, by water vapor reacting with carbon to form hydrogen and carbon monoxide. There are no gaseous compounds of nitrogen sufficiently stable such that this latter mechanism can be used to reduce the nitrogen level. Nitrogen can be reduced effectively only by decomposition or by adding a constituent - such as niobium, zirconium, titanium, hafnium, or uranium - that forms a strong nitride. These metals can form nitride precipitates and can effectively lower the nitrogen content in solution rather markedly. Nitrogen content is a major problem in these metals. Searcy and Finnie have computed Sievert's Law Constants for the solubility of nitrogen in a number of transition metals at their melting points as eutectic points[21]. If one considers that the vacuum furnace is well trapped and produces an ultimate vacuum of about 1 micron it is reasonable to suppose that this gas may be mostly nitrogen, hence a system pressure of about 10^{-6} atm is a realistic estimate for the nitrogen partial pressure in such an evacuated chamber. Table 3 shows the temperature of the calculation, the Sievert's Law Constant, and the concentration in ppm atomic for a number of transition metals. The values in the above table may be utilized to compare a

predicted value with the basis of experimentation. Simkovich has presented values for nitrogen content of a number of alloys after prolonged heating in vacuum[22]. In many cases there was little evidence that the ultimate composition had been reached although the rate of release of nitrogen had fallen. Most of the alloys he considered contained 15-percent chromium, hence one would assume (on considering an ideal solution) that the ultimate nitrogen content could go as low as about 20 ppm. He shows something over 30 ppm after 96 minutes at 2800 F and a pressure of 5 microns. The presence of 4-percent titanium results in a nitrogen retention of about 110 ppm at 96 minutes, and the curve indicates that the nitrogen level is not decreasing. Actually one would predict that 4-percent titanium would increase the nitrogen level to possibly 1000 ppm if the titanium behaved as an ideal solution. Semiquantitatively then, one can estimate the amount of nitrogen based on the concentration of chromium as well as any of the strong nitrate formers in table 3. If activities of the components in the metal are known, then the computation can be made quantitative.

TABLE 3. - NITROGEN LEVEL ATTAINABLE IN 10^{-6} ATM NITROGEN RESIDUAL PRESSURE[21]

Element	Temp, C	Sievert's Constant, $k = X_N/P_{N_2}^{1/2}$	Attainable Purity, ppm (atomic)
Ti	1670	8.50×10^1	>100,000
Zr	1850	3.20×10^1	>100,000
Hf	2230	8.23	>100,000
V	1920	1.26	1,300
Nb	1965	1.57	1,600
Ta	2690	2.25×10^{-1}	225
Cr	1900	1.35×10^{-1}	135
Ni*	1500	3×10^{-5}	0

*Added to original table.

Oxygen removal in melting. - Oxygen removal is more complex due to the existence of gaseous oxide vapor species. In some cases - uranium, tungsten, and molybdenum for example - it is possible to purify the metal by preferential volatilization of an oxide impurity. At the other extreme - the alkali metals - the metal must be distilled away from the impurity. Brewer and Rosenblatt have analyzed a number of metals and have established a parameter, R, which is a measure of how well oxygen can be removed by volatilization of an oxide impurity.[23] R is defined as $(O/M)_{vapor}/(O/M)_{metal}$, where O/M is the oxygen-to-metal ratio. A high value for R indicates that oxygen can be readily removed by vaporizing out an oxide impurity. A very low value for R implies that the metal can be purified by distilling the pure metal from its residual oxide. Nickel is an example of a metal for which purification by volatilization is not practical. They conclude that R = 10 for nickel at 1450 C. This would require that 10 percent of the metal be vaporized to reduce the oxygen content to 1/2 its

original value. As a generalization, values of R of a hundred or greater indicate that oxygen can be removed by volatilization of an oxide impurity. Values of R of one-hundredth or less indicate that a pure metal may be obtained by distillation. Table 4 lists values of R, the mole fraction at saturation, and the vapor pressure of the metal at temperature T for a number of elements.

From table 4 one can conclude that the alkali and alkaline earth metals may be purified by distilling them and that the 4th Group refractory transition metal can be purified by preferential volatilization of an oxide or even through the loss of monatomic oxygen for molybdenum, tungsten, and rhenium. For the transition metals, it is not practical to purify by these means. It is possible, however, to utilize silicon or carbon to remove oxygen. As an example of how silicon could be utilized, consider a molten melt containing about 50-percent iron to which about one-percent silicon had been added. It would be anticipated that silicon would not behave ideally in the melt but rather it should show negative deviation from ideal behavior. If the activity of the silicon is 0.001 or thereabouts, one can compute the efficacy of silicon in cleaning up an iron alloy. Based on free-energy values[24] for iron saturated with oxygen at 1810 K, one calculates the partial pressure of oxygen (O_2) in equilibrium with the melt to be about 2×10^{-9} atm.* It necessarily follows that the partial pressure of oxygen in the furnace must be less than this value if any purification of the melt is to occur. One then calculates from the X_o in table 4 a Sievert's Law constant of k = 200 for Fe at 1810 K. Based on the free energy of formation of $SiO_{(g)}$ at 1800 K one calculates that $pSiO/(aSi \times pO_2)^{1/2}$ in these two expressions to obtain $X_o = 1.2 \times 10^{-5}$ pSiO/aSi. If the activity of silicon is about 10^{-3} in the melt, then $X_o = 1.2 \times 10^{-2}$ pSiO. In the original melt in which X_o was about 10^{-2} then pSiO can be nearly atmospheric pressure. Boundary layer reaction and other kinetic hinderances would prevent this rate being realized, but it would be reasonable to expect silicon to effect a reduction in the oxygen content of the melt by at least two orders of magnitude. A similar analysis can be made for additions of carbon, tin, or germanium which should also prove effective. This analysis can be considered at least semiquantitatively correct and certainly should be indicative of the potential purity of product possible through vacuum melting.

*Atomic oxygen pressure is 5×10^{-9} atm; however, for this illustration molecular oxygen is employed.

TABLE 4. - VAPORIZATION OF OXYGEN SPECIES FROM METALS

Metal	Temp, K	P_{metal}, atm	X_O, saturated Mole Fraction O	R at X_O
Si	1685	$10^{-6.3}$	$10^{-3.7}$	10^{8}
Sm	1000	10^{-10}	10^{-2}	$10^{6.3}$
Nb	2740	$10^{-5.6}$	10^{-4}	10^{3}
Ta	3250	10^{-5}	$10^{-3.4}$	10^{5}
Ti	1940	$10^{-5.2}$	$10^{-0.47}$	1
V	2190	$10^{-4.4}$	$10^{-0.47}$	10
Cr	2171	$10^{-2.2}$	10^{-2}	$10^{0.5}$
Fe	1810	$10^{-4.5}$	$10^{-2.2}$	$10^{0.4}$
Co	1765	$10^{-5.1}$	$10^{-2.1}$	10
Ni	1726	$10^{-3.4}$	$10^{-2.1}$	10
Be	1556	$10^{-3.4}$	10^{-3}	10^{-6}
Li	1000	$10^{-1.6}$	10^{-3}	10^{-8}

Process Selection Considerations

The major melting and casting techniques currently used in the production of superalloy materials have each been separately discussed. The principal commercial techniques that have been reviewed are vacuum induction melting, vacuum arc melting, and investment casting. In addition to these, the discussion has included electroslag melting, which has found only limited commercial acceptance to date, and electron-beam melting which has not yet been used for the commercial production of superalloy materials but is believed to have sufficient potential to be included in this discussion. The remaining task is the comparison of the various melting and casting techniques for specific applications.

The choice of melting techniques for superalloys depends upon many considerations including the characteristics and composition of the alloy in question as well as the desired characteristics of the finished part. Some important considerations are the segregation tendency (alloy content) of the superalloy, the desired ingot size, purity and mechanical property requirements, reactivity and vapor pressure of the alloying additions, etc. In those instances in which a significant cost differential exists between competing processes, cost will certainly influence the choice of a particular

technique, and at times a compromise must be made between ingot quality and cost.

In this section consideration is given to various melting and casting techniques that have become competitors to some degree in the superalloy industry. An attempt is made to discuss the advantages and disadvantages inherent in competing processes in an effort to develop a basis for selecting the best technique for a given application.

Vacuum melting versus air melting. - A primary reason for the vacuum melting of superalloys is to lower the gas content of the alloys by the elimination of potential sources of contamination. The electric-arc furnace provides three major sources of contamination: refractory crucibles, the slags, and the air atmosphere. In vacuum induction melting, refractory crucibles are still typically used; however, the slags and the air are eliminated as potential sources of contamination. In this technique, oxygen is eliminated as a gaseous product by reactions with carbon or hydrogen, and the vacuum system removes the products from the chamber. In vacuum arc melting, all three sources of contamination are eliminated since melting is performed under vacuum in a water-cooled copper crucible. The advantages of low-oxygen-content superalloy materials have been indicated by Jones[25] in a study in which he related the rupture life of Udimet 500 to the oxygen content of the alloy in trace amounts (figure 4). As the oxygen content is decreased below about 50 ppm, there is a marked increase in the stress-rupture life of this nickel-base alloy. Decreasing gas content in these alloys not only improves the high-temperature strength, but also results in significant increases in ductility and workability as well as decreasing the transition temperature between ductile and brittle behavior and improving electrical and magnetic properties[26]. Another advantage offered by vacuum-melted materials is the extremely beneficial effect of boron on the mechanical properties of superalloys when it is present in trace amounts[26]. This effect of boron is noted for both vacuum- and air-melted materials; however, boron composition is much more easily controlled in vacuum melting because of the absence of boron-oxygen reactions observed in air-melted materials. For vacuum melting, boron may be added after the melt has been deoxidized. The effect of boron on superalloy materials is demonstrated in figure 5 by the increase in stress-rupture life and ductility in Waspaloy with trace additions of boron. As little as 15-ppm boron is sufficient to double the stress-rupture life and percent elongation exhibited by this material.

In addition to decreased gas contents of vacuum-melted materials, this technique has provided the opportunity for making several minor but highly significant chemistry modifications. The elimination of manganese and silicon deoxidants in air-melted materials from nominal compositions of these materials has provided definite improvements in the high-temperature properties of superalloys, especially their ductility[27]. In addition to this, the improved ductility of vacuum-melted materials has provided the opportunity for increasing the total titanium and aluminum

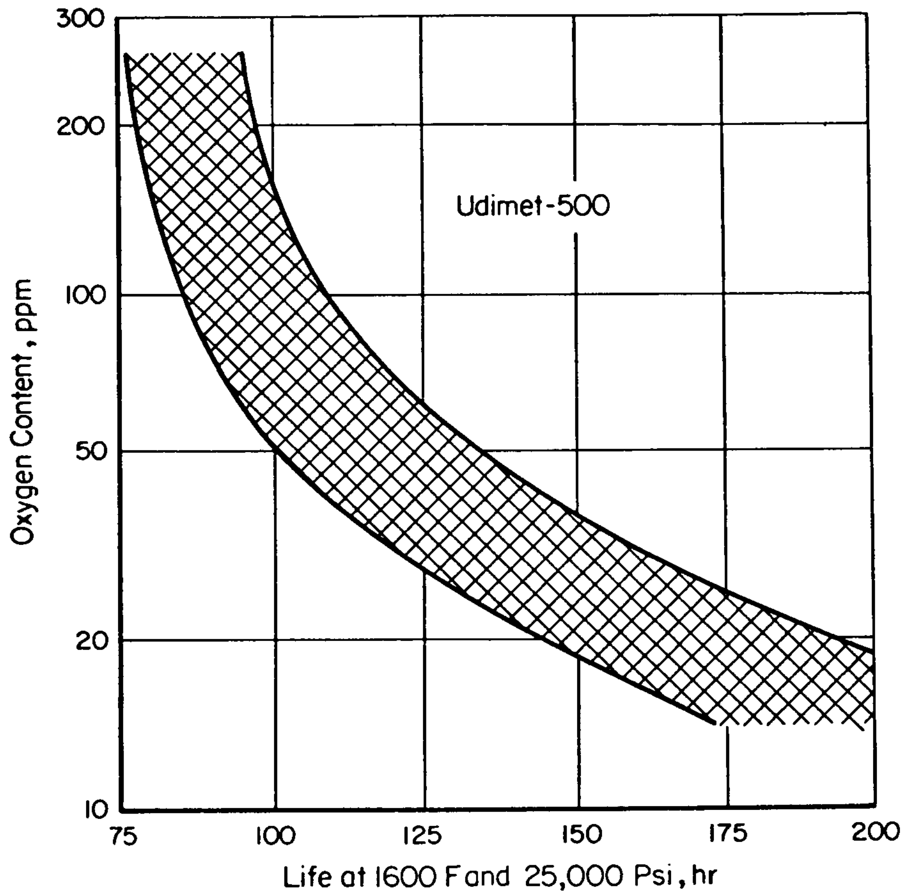


FIGURE 4. OXYGEN CONTENT OF UDIMET 500 VERSUS STRESS-RUPTURE LIFE AT 1600 F AND 25,000 PSI[25]

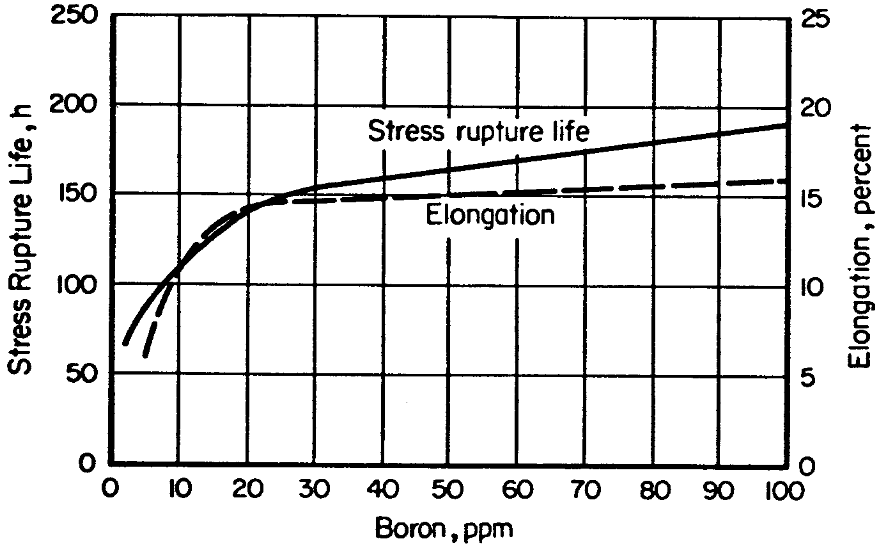


FIGURE 5. EFFECT OF BORON ON THE DUCTILITY AND STRESS-RUPTURE LIFE OF WASPALOY[26]

contents in these materials[27]. These constituents participate in the formation of gamma prime Ni_3 (Al, Ti) to produce significant increases in the high-temperature strengths of these materials.

It is apparent that vacuum melting represents a significant improvement over air melting for the preparation of superalloy materials, especially those containing significant amounts of aluminum and titanium. The sole advantage that air melting has to offer for the preparation of these materials is its economical operation; vacuum melting is an inherently more expensive technique than air melting because of the more sophisticated equipment required. Darmara has pointed out that a fair comparison between air and vacuum melting cannot be determined on the basis of the cost of the melting operation alone[28]. Technical considerations, such as the rigidity of the specifications to be met, must also be considered. With rigid specifications it would be more difficult to meet these specifications by air melting than by vacuum melting. A higher volume of scrap material results for the air-melting route. In this situation the high cost of vacuum melting will be partially compensated for a decrease in the total volume of scrap produced. The savings resulting from decreased scrap volumes is obviously related to the severity of the buyers specifications. Thus, vacuum-melted material may be economically advantageous for materials prepared to rigid specifications. In many cases these specifications will only be met by vacuum-melted materials.

Vacuum induction melting versus vacuum arc remelting. - The two vacuum-melting techniques differ in practically every respect except that both are conducted in vacuum atmospheres. It, therefore, is not surprising that the products produced by each technique are considerably different with respect to quality and application. The most important justification for vacuum induction melting is that, of all the melting techniques considered, it provides the greatest degree of control over composition[26]. The primary reasons for this are the stirring generated by the eddy currents in the melt and the long time to complete the refining reactions. Inductive stirring both homogenizes the melt and brings reactants to the melt-vacuum interface where reactions can proceed rapidly. The long length of time for which the charge can be maintained in the molten states provides several advantages. First, it provides sufficient time for sampling and subsequent additions to the melt to maintain exact composition. This ability to maintain accurate control of composition increases the ability to reduplicate heats to extremely close specification ranges. Machlin has considered the kinetics of deoxidation reactions in vacuum induction melting and concluded that deoxidation occurs in two steps[29]. The first is by boiling in the melt and the second by the later elimination of CO at the melt-vacuum interface by diffusion through the melt adjacent to the interface. During deoxidation, boiling accounts for the major loss of oxygen from the melt; however, the second stage (diffusion of CO) is equally important because of the further decreases in oxygen content of the melt which are possible. Long times are required for this diffusion-controlled elimination of oxygen from the melt. For example, it has been reported that about 30 minutes are required to

reduce the oxygen content of low-carbon iron from about 200 to 20 ppm by induction melting[26]. Thus, the long melting time made possible by vacuum induction melting results in lower oxygen contents of these materials. In addition to these advantages, further advantages are that the degree of superheat to the melt may be controlled closely and that the metal is cast under conditions which are very similar conventional casting operations[30]. The use of the refractory mold for vacuum induction melting represents a disadvantage in that reactions between the melts and the refractory crucibles are generally observed. The primary reaction observed is the transfer of oxygen from the refractory crucible to the melt, thus establishing an equilibrium oxygen content in the melt which corresponds to the value at which the rate of deoxidation equals the rate of oxidation from the crucible.

As opposed to the chemistry-related advantages offered by vacuum induction melting, vacuum arc remelting offers certain advantages to the production of superalloy materials which are related to the structure of the ingots produced. The structural advantages presented by this technique are in general related to the comparatively small volume of material which is molten at a given time and the directional nature of the solidification of the ingot. These two factors result in reduced dendritic segregation and microporosity and, in general, result in columnar grain structures oriented approximately parallel with the direction of solidification. Vacuum-arc-melted ingots typically have better mechanical properties than those prepared by vacuum induction melting. Of particular importance is the increased fabricability of ingots produced by arc melting. The degree of composition control in vacuum arc melting is considerably restricted because the electrode must be essentially of the desired composition. Volatile elements will be removed to some extent and must be overcharged; with vacuum induction melting, volatile alloying additions can be made just prior to casting and, if necessary, under an inert gas. Mold reactions are eliminated with vacuum arc remelting because of the use of a water-cooled copper crucible. The reduced segregation and microporosity observed in vacuum-arc-remelted ingots results in the ability to produce larger ingots; for highly alloyed superalloys, excessive segregation limits the maximum ingot size to approximately 24 in. diameter. Vacuum induction melting on the other hand is capable of producing sound ingots with low segregation only for small ingots (under ≈10 in. sq.)[30].

Because of the different capabilities of these two melting techniques, the choice of which process to use is rarely difficult and the economics of the two processes are not generally an important criterion. It is, however, generally accepted that vacuum induction melting is a more expensive technique than is vacuum arc remelting.

The trend in recent years has been toward the double vacuum melting of superalloy materials. The process is started with vacuum-induction-melted material that is cast into electrodes and then vacuum arc remelted. This technique is standard operating procedure for the more highly alloyed

superalloy grades from Incoloy 901 on up. Even such trades as A-286* and V-57* are frequently melted by this technique. This is especially true when a high percentage of scrap metal is to be used. Double vacuum melting combines the advantages of the vacuum-induction and vacuum-arc-melting techniques. That is, the close composition control afforded by vacuum induction melting is combined with the improved ingot structure provided by vacuum arc melting.

Vacuum arc remelting versus electroslag remelting. – The two consumable melting techniques are extremely similar in many respects; however, two features serve to distinguish the two melting techniques. First, vacuum arc remelting is conducted in a vacuum atmosphere while electroslag melting is typically conducted in air under a slag blanket. Second, the heat source in vacuum arc remelting is a high-temperature arc-plasma generated between the electrode and the melt, while in electroslag melting the heat source is a resistively heated molten slag. As opposed to the large differences in structure of ingots produced by vacuum induction or vacuum arc melting, the difference between ingots produced by vacuum arc and electroslag melting is one of difference in degree. That is, both techniques produce a directionally solidified product with reduced microsegregation and porosity; however, both effects are enhanced by electroslag melting. The increased tendency toward directional solidification in electroslag melted materials is due to the shallow molten pools typically obtained as well as to the slag skin that forms on the inside surface of the water-cooled copper crucible. In addition to these effects, segregation is limited in electroslag melting because of the more uniform and quiescent melting conditions. Electroslag melting typically results in cleaner macro- and microstructures in similar size ingots with better uniformity of physical and mechanical properties. For many materials significant improvements in hot workability and machinability are experienced for electroslag-melted materials. The primary problem associated with this technique is the choice of appropriate slags. Although several slags appear to have general applicability to many types of materials, the appropriateness of a given slag must be demonstrated for each material before commercial utilization can be made. With the slags used to date, the elimination of oxide inclusions from the ingots has typically not been as good as that experienced with vacuum arc melting.

Economic comparisons between vacuum arc remelting and electroslag remelting have been made by several investigators. The most recent is that by Duckworth and Wooding of the British Iron and Steel Research Association and Consarc Corporation, respectively[31]. They have considered the relative costs of producing 24-in. diameter ingots under each technique, assuming that the equipment was designed for the specific purpose for which it is being used and assuming that all modern techniques of automation and rapid turnaround have been used. Table 5 compares the annual operating costs for twin 24-in. furnaces. It can be seen from this table that

*Iron-base superalloys.

TABLE 5. – ANNUAL OPERATING COSTS VAR AND ESR TWIN 24-INCH FURNACE INSTALLATION[31]

Unit Cost	VAR	ESR
Direct Labor Cost - Two Men, 15 Shifts (one operator and one helper can comfortably operate two automated furnaces)	\$ 48,000	\$ 48,000
Manufacturing Overhead - U. S. Average Two Furnaces (including G and A and maintenance, lighting, heating, and indirect services at 140 percent of labor cost)	\$ 67,000	\$ 67,000
Melting Power Cost		
0.3-0.5 kwh/lb (assuming average of 0.35 kwh/lb, 1000 lbs/hr, 1.2¢/kwh, 15 shifts per week, 50 weeks per year)	\$ 23,000	
0.4-0.6 kwh/lb (assuming average of 0.5 kwh/lb, 1250 lbs/hr, 1.2¢/kwh, 15 shifts per week, 50 weeks per year)		\$ 42,500
Cooling Water Cost With Recirculating Water System	\$ 3,500	\$ 4,100
Depreciation 10-Year Straight Line Based on Installed Capital Cost (2 VAR 24 in. Furnace, \$480,000; 2 ESR 24 in. Furnace, \$384,000; cost includes furnace power supply, crucibles, foundation and structural steel work)	\$ 48,000	\$ 38,400
Depreciation 20-Year Straight Line on Building and Services (assuming 1,000 sq ft per furnace at \$25.00 a sq ft capital cost \$50,000)	\$ 2,500	\$ 2,500
Slag Cost (at 0.4¢ per lb of metal melted, assuming molten slag start)		\$ 28,000
Total Annual Operating Cost	\$ 192,000	\$ 230,500
Total Annual Production, lbs	5,600,000	7,000,000
Total Cost, cents per pound	3.4	3.3

TABLE 6. - COST ANALYSIS ESR MULTIPLE AND SINGLE INGOT MELTING SIX 8-INCH DIAMETER INGOTS(31)

Unit	6 ESR Twin Suspension Furnaces	1 Twin Suspension Multiple Furnace
Labor - 15 Shifts (three operators and three helpers to run six furnaces)	$144,000	
(one operator and two helpers to run multiple furnace)		$ 72,000
Manufacturing Overhead (including G and A, maintenance, lighting, heating, and indirect services at 140 percent of labor cost)	$200,000	$101,000
Power Cost at 0.5 kwhr/lb (melt rate 400 lbs/hr, 1.2¢/kwhr, 15 shifts per week, 50 weeks per year)	$ 86,000	$ 86,000
Cooling Water Cost with Recirculating System	$ 8,000	$ 8,000
Depreciation 10-Year Straight Line Based on Installed Capital Cost (6 ESR Furnaces, $495,000; 1 Multiple Furnace, $275,000)	$ 49,500	$ 27,000
Depreciation 20-Year Straight Line on Building and Services (assuming 800 sq ft per single furnace and 1600 sq ft for multiple furnace at $25.00 a sq ft; 6 ESR Furnaces, $120,000; 1 Multiple Furnace, $40,000)	$ 6,000	$ 2,000
Slag Cost (0.4¢ per lb of metal melted, assuming molten slag start)	$ 57,200	$ 57,200
Total Operating Cost	$550,000	
Total Production, pounds	14,300,000	
Total Cost, cents per pound	3.8	2.47

the higher production rate offered by electroslag melting (assumed to be an average of 25 percent greater because of the pool-volume relationship) is substantially offset by the higher specific power required and the cost of the slag itself. The total cost in the United States for high quality slags in the calcium fluoride-lime-alumina family are estimated at $0.16 a pound in the liquid state ready for molten slag starting. With a metal-to-slag ratio of 40 (by weight), this gives a slag cost of approximately 0.4 cents per pound of metal melted.

Using this basis of comparison, it can be seen that the electroslag remelting provides only a slight economic advantage over vacuum arc remelting. The economic factors can be weighed more heavily in favor of electroslag melting, however, if multiple-ingot electroslag melting (previously discussed) is considered. Table 6 compares the cost of producing 8-in. diameter ingots of high-speed steel. This is a segregation-sensitive material that is limited by melting-rate considerations to a production rate of ≈400 lb per hr for this ingot diameter. The comparison in table 6 is for the electroslag melting of six ingots in six single-ingot furnaces as opposed to one multiple-ingot furnace. The economic advantage provided by multiple-ingot melting is obvious from this table.

The difference between ESR and VAR in cost per pound is generally not alone sufficient to justify the transfer from vacuum arc to electroslag melting. In addition, producers of ESR materials have found it difficult to compete with vacuum-arc-melted products because of rigid specifications on gas contents and inclusion counts. For these reasons, electroslag melting has not yet become a serious competitor with vacuum arc melting. However, significant property improvements (especially hot workability) have been achieved for several electroslag-melted superalloy materials. Under these conditions conversion to electroslag melting is favored.

<u>Electron beam melting versus other vacuum-melting techniques</u>. - The primary advantages of electron-beam-melted materials are attributable to the typical high purity of the product resulting from melting in a high-vacuum environment. Electron-beam-melted materials typically have higher ductility and lower strengths than materials produced by other vacuum-melting techniques as a result of the reduced interstitial impurity content. For the electron beam melting of superalloys of lower strengths can probably be compensated for by increased aluminum and titanium additions which should result in improved high-temperature strengths for these materials.

The classical problem associated with the electron beam melting of alloys has been the preferential vaporization of the more volatile alloying additions. This problem certainly exists to some extent for the electron beam melting of superalloys; however, some preliminary studies at Airco-Temescal suggest that the vaporization loss of most elements is not as serious a problem as would be calculated from thermodynamic considerations. The reason for this behavior appears to be that the molten alloys

in many instances do not represent a reasonable approximation to ideal solutions, but rather interactions between the various elements in the melt result in more stable species than expected. The hearth melting furnace developed at Airco-Temescal provides an advantage for the handling of volatile alloying additions, in that these elements can be continuously added to the melt just ahead of the point at which the molten charge enters the mold. This restricts vaporization loss by minimizing the length of time for which these elements are exposed to the high-vacuum atmosphere.

Another approach to minimizing vaporization loss of alloying additions is melting under the higher pressures possible with plasma electron beam melting. However, operating at higher pressures can be expected to produce a slightly lower-purity product than can be produced by high-vacuum electron beam melting. This technique, to some extent, represents a compromise between the purity produced by high-vacuum electron beam melting and the composition control achieved by more conventional low-vacuum-melting techniques.

The economics of electron beam melting on a relatively small scale are highly unfavorable as compared to other vacuum-melting techniques. However, Hunt and Smith have shown that hearth electron beam melting has a very favorable scale-up potential and that for large-scale melting operations, electron beam melting may compete with the more standard vacuum-melting processes on an economic basis(32). Table 7 shows the approximate distribution of operating costs for typical medium- and large-scale electron-beam processing systems by their analysis. This treatment is for the melting of iron-base alloys; however, the comparison to nickel-base superalloys is expected to be good. The smallest scale unit, capable of producing 15,000 tons per year at 2000 kw of electron beam power, has an operating cost of just under 2.50 cents per pound. This cost is reduced to less than 1.0 cent per pound for a 10,000 kw furnace capable of 100,000 tons per year.

Table 8 shows the estimated installed capital costs for the units in table 7. Note that the cost per pound as well as the cost of the electron-beam systems, relative to the vacuum and materials-handling systems, decreases with the size of the unit. For the 10,000 kw furnace the operating cost plus capital equipment costs would result in a total cost of approximately 5.0 cents per pound. At this cost it will compete favorably with vacuum induction melting for the production of superalloy materials(33).

Vacuum casting versus other techniques. - In this section we consider the relationship of vacuum-casting costs to those of other methods of making a part. Technical requirements are sometimes overriding, and then no method but vacuum casting will suffice. But sometimes there is a choice, depending greatly on the size of the production run. Determination of the cross-over point between precision casting and other processing is an important step in determining the choice of method.(34)

TABLE 7. – APPROXIMATE DISTRIBUTION OF OPERATING COSTS FOR A TYPICAL FAMILY OF SINGLE MEDIUM- AND LARGE-SCALE ELECTRON-BEAM PROCESSING SYSTEMS(32)

	2,000 kw Capacity(a)	10,000 kw Capacity(b)
	Dollars per Year	
Labor & overhead	350,000	500,000
Utilities	200,000	850,000
Maintenance	150,000	450,000
Total	700,000	1,800,000
	Cents per Pound	
Labor & overhead	1.17	0.25
Utilities	0.67	0.43
Maintenance	0.50	0.22
Total	2.34	0.90

(a) Specialty steel ingot production 15,000 tpa.
(b) Stainless steel ingot and slab production, extra-low-carbon grade 100,000 tpa.

TABLE 8. – ESTIMATED APPROXIMATE CAPITAL COSTS (INSTALLED) FOR UNITS IN TABLE 7(32)

	2,000 kw Capacity	10,000 kw Capacity
Electron-beam systems, $	1,300,000	5,000,000
Vacuum systems, $	500,000	1,600,000
Materials-handling systems, $	700,000	1,800,000
Total, $	2,500,000	8,400,000
Total, ¢ per pound	8.3	4.2

A typical cost comparison would be made by plotting cost per piece against the number of pieces to be made. Below, some of the main costs for making the calculations are tabulated. Figure 6 shows the comparison for two processes.

	Mainly Variable Cost	Mainly Fixed Cost
Machining		
Tools and set-up	X	
Tool maintenance		X
Actual machining	X	
Material costs*		X
Forging		
Tools and set-up	X	
Tool maintenance		X
Actual forging	X	
Material costs*		
Machining of final part (Tools, maintenance, actual machining time)	X	X
Inspection		X
Investment Casting		
Tools and set-up for pattern	X	
Tool maintenance		X
Actual casting cost		X
Materials cost		
Patterns	X	Some losses of material
Molds, crucibles		X
Alloy (minus scrap recovery)		X
Machining of final part		
Inspection		X

*Basic cost less scrap credit. Quantity discounts make this cost slightly variable.

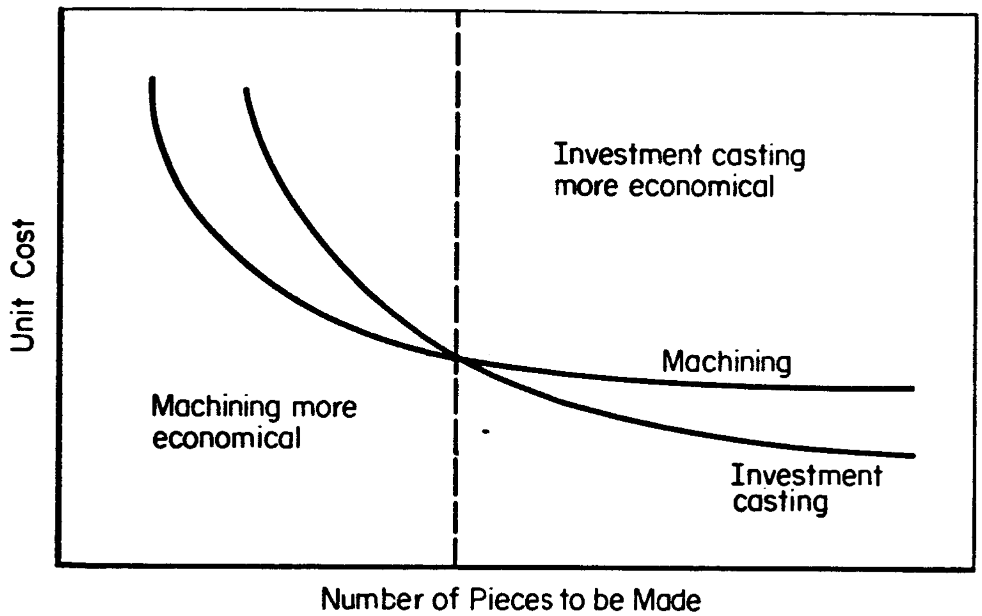


FIGURE 6. REPRESENTATION OF THE COSTS OF COMPETITIVE PROCESSES[34]

CHAPTER 5. CURRENT AND POTENTIALLY IMPORTANT MELTING PROCESSES

Vacuum Induction Melting

During the last 50 years, induction methods have been used widely in industry for heating and melting metals. An induction-melting circuit is fundamentally a transformer in which an inductor carrying the alternating current serves as a primary and the material to be melted is made the secondary by simply placing the material, or a conductive element containing the material, in the alternating field of the inductor without any electrical contact being made. The magnetic field lines of the inductor intercept the surface of the electrically conductive material being heated and induce electrical energy in the material. The described heating effect takes place primarily in the surface layers of the heated material. The depth of penetration of the field is governed by the frequency of the current used to produce the alternating field.

Because the induction coil is not in contact with the material being melted, it can be kept at a low temperature. The induction coil is normally constructed of a hollow conductor through which coolant is continuously circulated. The maximum temperature obtainable for melting is solely a function of the amount of energy that can be coupled to the material being heated, of the materials used in the construction of the furnace, and of the furnace environment.

Vacuum induction melting is performed in an induction furnace situated in a vacuum chamber. Its chief advantages are simplicity and an ability to control composition very closely. Normally an ordinary refractory crucible and standard ingot molds are employed. In vacuum induction melting, certain alloying additions, not possible in air, can be made to the melt. Because the melt is stirred by induced currents, equilibrium conditions can be achieved soon after alloying additions are made.

The principal disadvantages of vacuum induction melting concern the crucible and the structures obtained in castings. At low pressures the reactions between the melt and the crucible proceed at a much more rapid rate than at atmospheric pressure; as a consequence, a higher level of impurities from the crucible is often observed in vacuum-induction melts than in air-induction melts. In casting, center segregation in the solidifying ingot is another problem. Since melts are tilt-poured into molds and solidification usually proceeds slowly, an ideal solidification pattern is normally not obtained. The problem can be minimized somewhat by proper mold design and cooling practice, but, for the most part, it cannot be eliminated entirely, especially in large ingots.

The development of vacuum induction melting. – Construction of the first experimental vacuum-induction furnace is generally believed to have occurred sometime during the latter part of the 19th century. The adoption of vacuum induction melting on a production scale, on the other hand, did not occur until several decades later. The first production vacuum induction furnaces were small, but by 1939, heats as large as 10,000 pounds were melted in vacuum furnaces. Unfortunately, the development of high-speed, high-vacuum pumping systems did not match progress in furnace design; consequently, the fullest benefits of the process were not realized at that time, since pressures of less than 2 mm mercury could not be maintained.

The oil-diffusion pump was developed about the time of the introduction of the first production vacuum-induction furnace. Early oil-diffusion pumps permitted furnaces to be operated at considerably lower pressures, but melt sizes were limited to a few pounds. Requirements for high-vacuum pumping installations for nuclear and medical applications during World War II led to the development of mechanical and oil-diffusion pumps offering much greater speed and reliability which, in turn, permitted the processing of larger melts at very low pressures.

One of the greatest advances in vacuum induction melting occurred in the early 1950's when a major supplier of bucket forgings for jet engines was experiencing difficulty in obtaining air-melted high-temperature alloy bar stock with properties consistent from heat to heat. This was a serious problem since ingot forgeability and resultant mechanical properties (i.e., stress-rupture life) varied considerably. Consequently, scrap rates were excessive and production schedules were impossible to meet. The alloys with the widest scatter were nickel-based alloys containing appreciable quantities of aluminum and titanium present as precipitation-hardening agents. Because of the extremely active nature of aluminum and titanium, it was suggested that vacuum melting might be employed to prevent the oxidation of these elements in an uncontrollable manner during the alloying and the pouring of the ingot. Several heats of Waspaloy prepared by vacuum induction melting were evaluated. The results were excellent. Not only was more consistency in physical properties obtained, but also the average stress-rupture life was increased by a considerable amount. As melting practices were improved, properties continued to increase to the point where the specification for Waspaloy was raised considerably.

It was not long before the distinct advantages of vacuum melting led aircraft manufacturers to specify vacuum-induction-melted alloys for buckets and blades. The demand for this material rose sharply, and larger furnaces were installed by superalloy producers. Before long, improved alloys were also developed. They had not only superior stress-rupture properties but also improved tensile strength at elevated temperatures. These properties made them attractive to designers of structural members in the missile field.

Furnace designs. - Two basic types of induction melting furnaces exist and both have been in use for over 50 years with only slight modifications in basic design. These are the core-type and the coreless-type induction melting furnaces.

A cut-away view of the core-type furnace is shown in figure 7. This furnace operates at power-line frequencies. It was developed originally for melting brass but has become popular for copper, bronzes, zinc, and aluminum. Recent design improvements have made this furnace suitable for melting iron-based alloys; only a few superalloys have been melted in this type furnace.

Heat for melting in the core-type furnace is produced by utilizing the principle of the short-circuited iron-core transformer. Alternating current is passed through a multiple-turn primary coil surrounding an iron core. The secondary is a loop of molten metal surrounding the primary and the core. Current flowing through the primary induces a much larger current in the metal loop whose resistance creates heat for melting.

The core-type furnace is the most efficient type of induction furnace because its iron core concentrates magnetic flux in the area of the molten loop, assuring maximum power transfer from primary to secondary. However, the essential loop of metal must be maintained continuously in the core-type furnace. If the loop is allowed to freeze, extreme care is necessary in remelting, because it may rupture and disrupt the circuit. Consequently, core-type furnaces are rarely permitted to cool.

The coreless induction furnace is shown in figure 8. This furnace operates at low, intermediate, and high frequencies - from 60 to 10,000 cps - and is unmatched for flexibility. Like the core-type furnace, it operates by transformer action, but in this case it is similar to an air core transformer. The primary coil induces current directly in the metal charge that is contained in an unobstructed crucible. There is no internal melting loop. The primary is a water-cooled, helical copper coil surrounding the outside of the crucible.

The cordless furnace can be started from cold, allowing it to be shut down as desired, and usually is emptied completely by pouring, greatly simplifying alloy changes. Superalloy melting is normally performed in coreless induction furnaces. The following discussions refer principally to coreless induction furnaces.

Another way of classifying induction furnaces is by the manner in which the molten charge is poured. Charges are normally either bottom-poured or tilt-poured. Furnace designs involving bottom pouring were popular in the early development of induction melting.

Today production furnaces are all of the tilt-pour design. These furnaces can be divided into those where only the crucible tilts and those

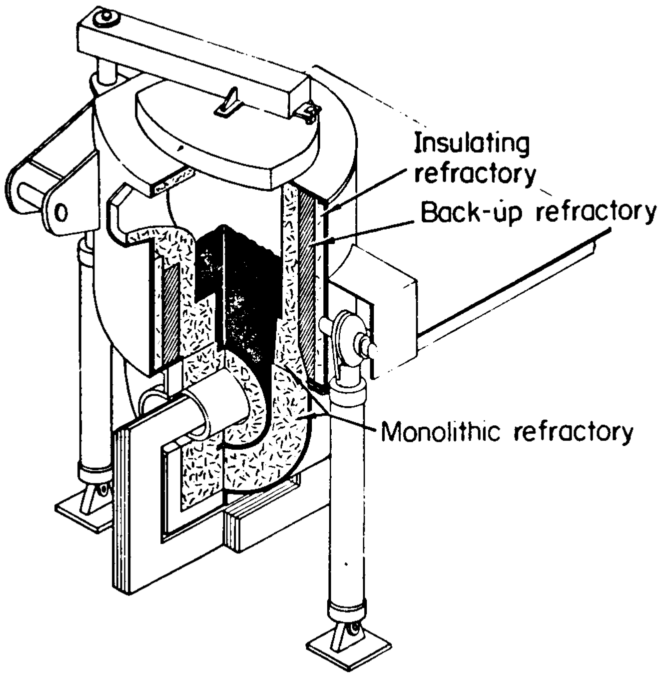


FIGURE 7. CORE-TYPE INDUCTION FURNACE

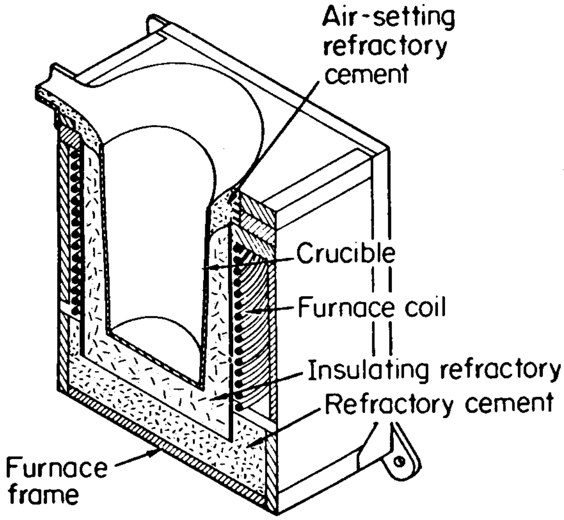


FIGURE 8. CORELESS-TYPE INDUCTION FURNACE

where the whole furnace chamber tilts. Cited advantages of the former are good visibility of the process during operation, ease of making additions, and good control during pouring. A schematic drawing of a furnace in which the crucible tilts is shown in figure 9.

The general design of an induction furnace depends upon its intended use and the size of the charge that is desired. Regardless of the size of the furnace, however, certain elements are basic to the design of all induction furnaces. These elements include the power supply, the crucible, the ingot mold and hearth, the furnace tank, the vacuum system, and auxiliary apparatus.

Power supplies: In general, the vacuum induction furnace is similar in design to its air-melting counterpart, except that the coil voltage rarely exceeds 450 V. The voltage is kept low to prevent corona and arcing, which tend to occur in vacuum at pressures in the range 10 to 500 microns on uninsulated coils. With the increase in furnace sizes that have occurred in recent years, however, the need for higher melting power has raised the coil currents to such values that at 400 V, the conductor size has become somewhat of a problem.

Coreless 180-cycle induction furnaces employ triplers, or special transformers, which triple line frequency to 180 cycles. Higher frequencies for melting applications are obtained with the use of water-cooled motor-generator sets. A good relationship usually exists between the size of a coreless furnace and its operating frequency. As a rule, a small furnace gives best results at high frequencies and a large furnace works best at the lower frequencies. A certain frequency is suited for a certain furnace when it gives good fast melting with a gentle stirring action. Too high or too low frequencies are accompanied by undesirable side effects. For example, at a frequency lower than ideal, a violent stirring action may occur that may produce inclusions of slag and refractory particles, as well as gas pickup. Excessive metal loss may also occur because of the increased surface area of the melt and the oxidation of volatile constituents. Startup may be harder, greater care may be necessary in charging, and in some cases, certain types of scrap, such as chips and turnings, may not be used for starting. Very important is that the life of the furnace lining can be reduced considerably by using too low a frequency.* On the other hand, if too high a frequency is selected for the size of the furnace, there may be a complete lack of stirring, uneven heating throughout the charge, excessive side-wall temperatures, and difficulty in attaining homogeneous melts. A recommended relationship between furnace size and frequency for alloy melting is as follows:

*It is not uncommon to reduce the life of the furnace lining by approximately 60 percent.

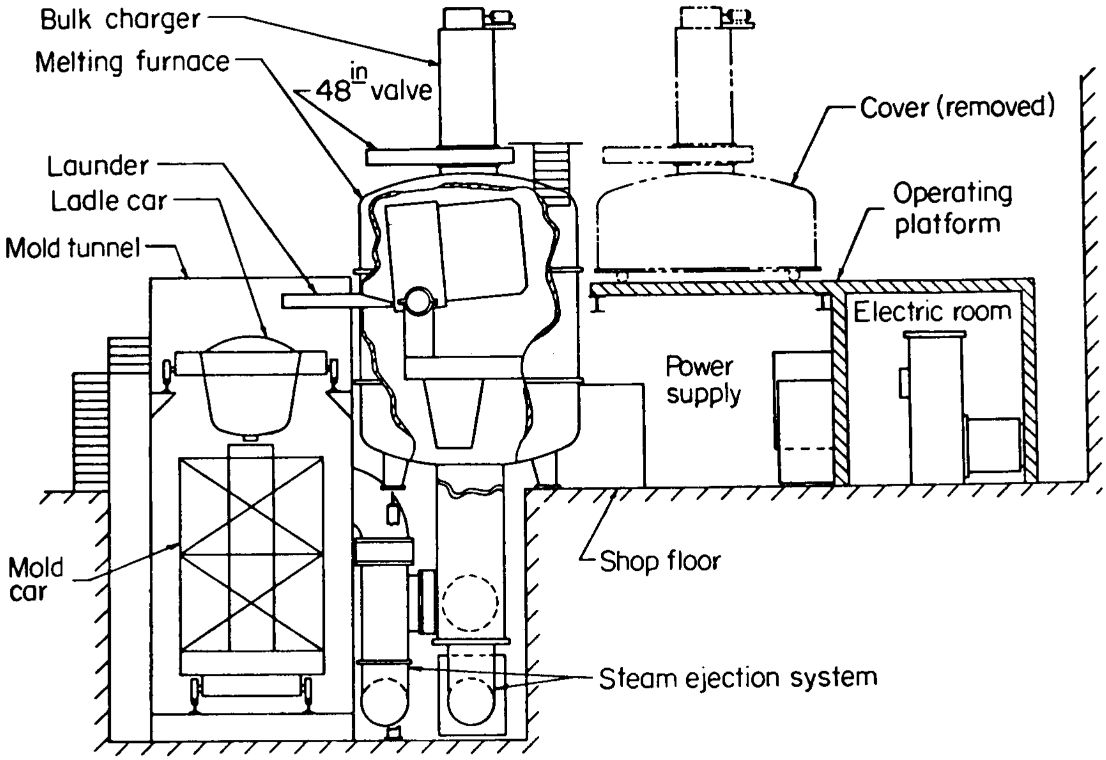


FIGURE 9. SCHEMATIC DRAWING OF A 30,000-POUND VACUUM INDUCTION MELTING FURNACE

(Courtesy Special Metals Corporation)

Furnace Size, lb per charge	Frequency, cps
2-50	10,000
12-500	3,000
200-4,000	1,000
3,000-15,000	180
8,000-20,000	60

The power requirements of vacuum induction furnaces increase with the size of the furnace and are influenced by the type of crucible and charge. To reduce melt-down time so that vacuum treatment of the liquid metal may begin, the power inputs are often larger than those for similar air-melting plants. The typical power supply for a furnace of 50 to 60 pounds capacity is 50 kw. A larger furnace of 5000-pound capacity might use up to 1100 kw.

Crucibles: Oxide ceramics or graphite are used almost exclusively for induction furnace crucibles. Because the molten metal reacts with the refractory, the type of reaction product may influence the choice of material. For superalloys, MgO, $MgO+MgO\cdot Al_2O_3$ spinel, and $MgO+Al_2O_3$ have found wide usage. MgO normally gives magnesium as the reaction product and the magnesium is usually vaporized away under vacuum conditions.

Crucibles are normally rammed and sintered in the furnace because crucibles thus formed are less expensive, have longer lives, are safer in use, and have better properties than prefired crucibles. The ideal crucible has a smooth, dense surface to reduce the reaction rate with the melt and is backed by a porous zone thick enough to give adequate thermal insulation and to allow any movements of the sintered region. The crucible, of course, must be strong enough to support the charge.

At present, the refractory most widely used for vacuum induction melting contains 70-percent magnesia and 30-percent alumina. In small furnaces (up to 300 lb), crucible lives of 50 or more heats are obtained with no difficulty. As the furnace size increases, however, the number of heats that can be made before a lining must be replaced decreases considerably. Much research is currently being done in efforts to increase crucible life by refractory manufacturers and by vacuum melters. The rapid growth of induction crucible size has caused a switch from monolithic linings to all-brick linings to achieve satisfactory service life for crucibles with capacities in excess of 10 tons. Usually, different grades of refractories are used for the working linings and backings of crucibles. Figure 10 shows a crucible containing a duplex lining currently used in a 30-ton vacuum induction furnace. The service life of brick-lined crucibles ranges from 25 to 45 heats for furnaces in the 15- and 30-ton capacity range.

Ingot molds and hearth: The molds in which the ingots are cast are very similar to those used in conventional melting shops; hot topping

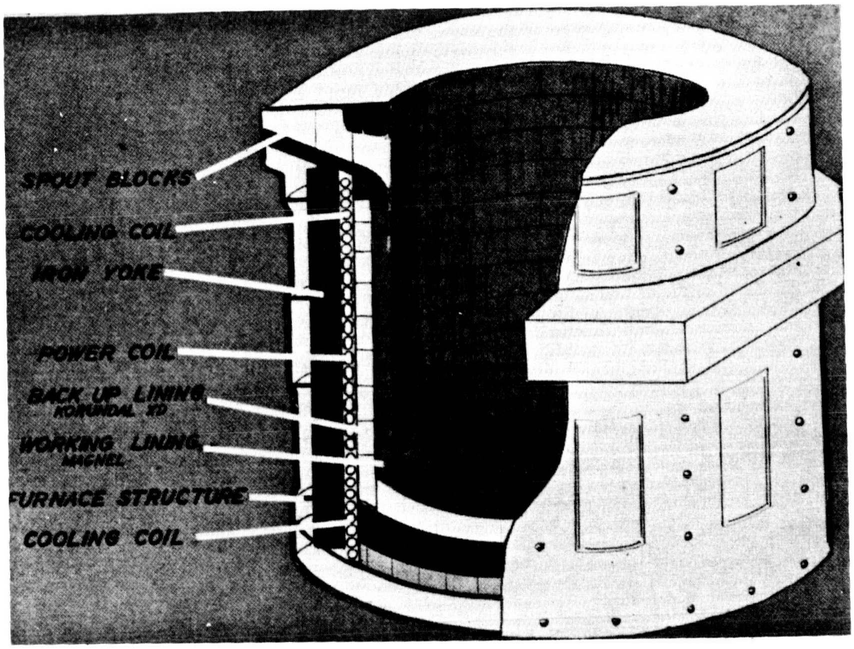


FIGURE 10. A SCHEMATIC REPRESENTATION OF A 30-TON INDUCTION CRUCIBLE WITH BRICK LININGS

(Courtesy of Latrobe Steel)

procedures include the use of refractory-lined hot tops, the use of exothermic linings, and the use of electric-arc hot toppings. The field of ingot casting still requires exploration to take advantage of one of the secondary features of vacuum melting – the ability to vary the pouring rate through wide limits with no possibility of contamination from the surrounding atmosphere. Advantages may be gained under certain conditions by very low pouring rates. Slow pouring can be accomplished with little difficulty in the vacuum chamber.

Another important aspect of the vacuum furnace is the hearth on which the molds are placed. In many early furnaces, little attention was given to the need for sufficient space to enclose the variety of ingot molds that are needed in production operations. Later, furnaces were improved considerably. Some included tunnel-like chambers with vacuum locks so that a procession of ingot molds could be moved into position, poured, and removed without breaking vacuum in the tank.

Furnace tanks: A tank or metal vessel is required to house the melt, crucible, molds, and associated equipment. Its size varies with furnace size and application. Small furnaces are easily enclosed in a vertical tank with a removable top cover. As furnace sizes increased and furnaces have been designed specifically for production applications, the vertical tank proved difficult to service between melts; therefore, most modern furnaces larger than 300 lb are enclosed in horizontal tanks, which provide much better access to the inner parts. A typical tank for a 2,000-lb furnace approaches 12 ft in diameter; larger furnaces require tanks of even greater size.

Vacuum system: Several sources of gas must be handled by the pumping system:

(1) The air present within the tank under normal conditions

(2) The air absorbed on tank walls, refractory linings, etc.

(3) Dissolved gases in the charge

(4) Gases resulting from reduction of oxides under vacuum

(5) Air leakage into the furnace.

The vacuum-pumping system must be designed to handle these various gas loads over a wide range of pressures. Two basic types of pumps are required: (1) mechanical pumps, to provide the pumping capacity from atmospheric pressure down to about 200 microns (at lower pressures their capacity decreases rapidly); and (2) oil-diffusion pumps, to handle gas loads in the 200-to-1 micron range. Oil-diffusion pumps remove gases from the chamber and compress them to a pressure such that they can be pumped to the atmosphere by mechanical pumps. Many diffusion pumps are available

in a wide range of sizes. It is possible to obtain a single pump to handle all the gas loads from a 2,000-lb furnace. A slightly different approach is being used on some larger furnaces. Instead of using one or two large pumps, several small pumps are connected to a large manifold. An example of such an arrangement is shown in figure 11. Also, in recent years, a significant development has been the steam ejector for use in large vacuum-induction-melting units. Instead of the standard combinations of mechanical and oil-diffusion booster pumps to cover the entire pressure range, steam-ejector pumping systems are being employed as roughing units in combination with oil-diffusion booster pumps.

Auxiliary apparatus: Examples of auxiliary apparatus include devices for making melt additions, melt samplers, temperature-measuring devices, and control systems. A very important feature in many vacuum furnaces is the additions device, which allows controlled quantities of a material to be added to the crucible at selected times during the melting cycle. Two main approaches used to make additions are:

(1) A system of cups (within the furnace) whose contents can be dumped into a chute

(2) A vacuum-locked chamber to hold the additive material.

In the very large furnaces, the second approach is most common.

To be certain that the chemical analysis of the final melt is within desired specifications, samples are normally withdrawn from the melt by dipping from the crucible and are removed through a vacuum interlock for spectrographic analysis. For proper control of temperature, two or more temperature-measurement devices are employed; disappearing-filament optical pyrometers and high-temperature dipstick thermocouples are commonly employed.

Complete reliability of all components is necessary to operate large-scale vacuum furnaces successfully on a production basis. Unlike conventional air-melting operations (where access is possible to practically all moving parts at any time), vacuum operations require that the melting furnace, tundishes, molds, and addition makers be isolated in a tank and be operated by remotely controlled manipulators. Mechanical failure may require the opening of the furnace for repair, which necessitates freezing the melt. This can be a costly operation because of lost time and the possibility of an improper ingot.

Most vacuum-induction melters employ a strict preventive maintenance program. Vacuum seals, bearings, valves, and electrical contacts are inspected and cleaned at frequent intervals; in some cases this cleaning is required after each heat. Dust deposits of evaporated metal, which collect on all cool surfaces within the melting chamber, are particularly detrimental and are usually removed after each cycle.

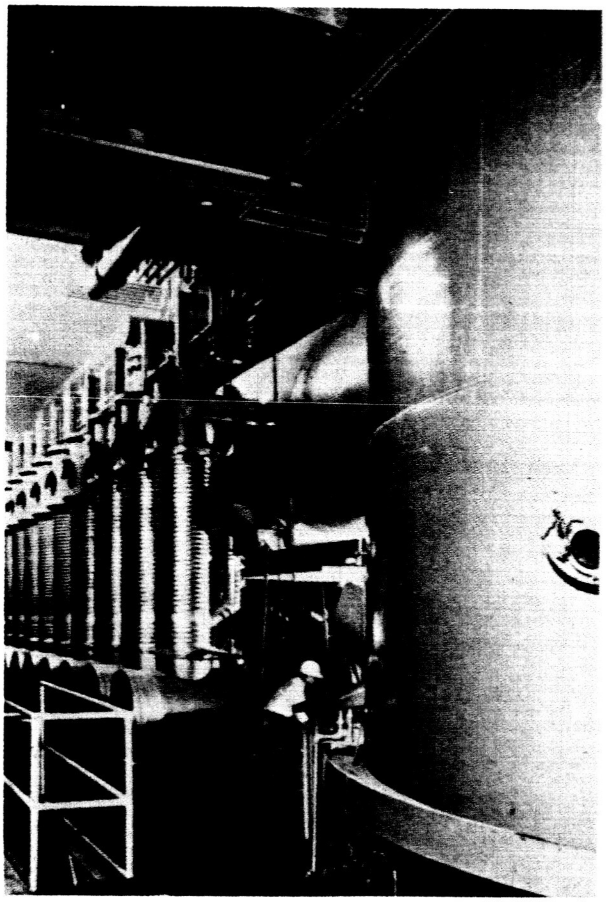


FIGURE 11. A ROW OF OIL-DIFFUSION BOOSTER PUMPS CONNECTED TO A TANK MANIFOLD

(Courtesy of Latrobe Steel)

Control of the melt. – Probably the most important metallurgical justification for vacuum induction melting is the composition control it provides. More exact composition control is afforded by vacuum induction melting than by any of the other known melting techniques. The term "composition" is meant to include not only the desired alloy additions but impurities as well. This control is achieved by vacuum induction melting because of the following capabilities:

(1) The ability to isolate the melt so that it can be treated as a system in the thermodynamic sense (Vacuum induction melting does this by preventing gases from outside the system from contaminating gases in the system.)

(2) The ability to control the pressure within the system

(3) Inductive stirring of the melt

(4) The flexibility to allow sufficient time for refining reactions to go to completion.

The advantages of vacuum induction melting accrue from these capabilities. In the simplest case, the melt is prevented from coming in contact with oxygen and nitrogen from the outside. Because of the lower pressure, i.e., by melting under a gas at pressures lower than atmospheric, it is possible to carry out reactions that, again, are not possible at atmospheric pressures. Inductive stirring plays two important roles. It homogenizes the melt composition, and it brings reactants to the melt-vacuum interface where the reaction can proceed rapidly to completion. The final capability, that of allowing time for the reaction to proceed, is extremely important and has not been sufficiently appreciated in the past. Because of the importance of vacuum-induction refining and the thermodynamic aspects of the process, these areas are discussed separately in another section.

Vacuum Arc Melting

In the vacuum-arc-melting process, the thermal energy of an electric arc is utilized in melting. Characteristically the arcs are high-current, low-voltage discharges. Purification and shaping of desired compositions are accomplished by melting the materials in vacuum and containing them in cooled metallic crucibles (generally water-cooled copper). The process consists of applying the arc heat to the surface of the molten metallic mass for a finite time in an atmosphere which has impurity partial pressures lower than that of the molten metal. These conditions result in the vaporization and removal of selected impurities from the metal under treatment. In addition, the large thermal gradients which exist between the chilled metallic crucible and the intensely hot melt surface cause directional solidification. This directional solidification is parallel with the heat flux and

results generally in a columnar grain structure. As a result, casting defects, such as gas holes and shrinkage cavities, are virtually eliminated. The process is normally carried out in a cylindrically-shaped crucible that is essentially a container inert to the metal under treatment.

Vacuum arc melting was originally devised for refractory metals (tungsten, tantalum, molybdenum) that are difficult to melt because of their high melting points, and for extremely reactive metals, such as titanium, hafnium, and zirconium. In recent years, the process has gained wide acceptance in the purification and structure control of the more common and commercially important metals (such as iron- and nickel-base superalloys) in spite of the fact that their melting points and chemical reactivities render them amenable to a number of more conventional melting and casting techniques.

<u>The development of vacuum arc melting</u>. - The starting point for the development of vacuum arc melting is usually credited to Sir Humphrey Davy, who produced the first man-made arc between carbon points. Robert Hare was probably the first person to apply the electric arc for metallurgical applications when, in 1839, he melted platinum and produced phosphorus, graphite, and calcium by chemical reactions in an electric arc within an evacuated enclosure. A furnace design, similar to that being used today for melting steel, was developed by Sir Walter Siemens in 1878 shortly after the invention of the dynamo. Siemen's furnace utilized carbon electrodes, a ceramic hearth, and an air-slag atmosphere.

In the early 1900's, vonBolton built the forerunner of the modern vacuum-arc-melting furnace. The three salient features of the original vonBolton furnace were the same as those utilized in present-day vacuum-arc furnaces; namely, (1) a high-temperature electric arc as a heat source, (2) a water-cooled, metallic platen or crucible to support the molten metal, and (3) a vacuum or inert-atmosphere enclosure in which the melting is carried out.

In vonBolton's design, as in present-day furnaces, the initial molten metal solidified the instant it came in contact with the highly cooled crucible. This solidified metal formed a shell or "skull" inside the original metallic crucible and subsequently functioned as the melting vessel itself. The molten metal was contained in the skull, and no interaction with or deterioration of the original liquid-cooled crucible occurred. The electrode that vonBolton used was not carbon, as earlier experimenters had used, but rather it was made of the metal to be melted.

Because of the heat generated in the electric arc, the electrode melted off in the form of very fine droplets. These droplets passed through the intense heat of the electric arc and accumulated as a molten pool in the skull, which was contained in the crucible. The crucible was part of the furnace structure, and the skull became an integral part of the metallic ingot being produced.

In 1935, R. K. Hopkins first utilized the cold-crucible principle and a consumable electrode in a large-scale commercial application. The resulting process, known as the Hopkins Process, was a departure from vacuum arc melting in that the molten metallic pool was not exposed to a vacuum but was covered by a molten flux which protected it from atmospheric contamination. In addition, the arc heating was replaced by resistive heating of the molten flux by the passage of the melting current. This commercially practiced melting technique, which is also known as the electroslag process or the electroflux-remelting process, is being used today to produce high-quality iron- and nickel-base alloys

In the same period, work was initiated by several investigators which eventually led to the technique as we know it today. Among these was Wilhelm J. Kroll who developed a technique to produce titanium ingots. The technique included the use of an inert atmosphere, a preformed consumable electrode, and a water-cooled metallic crucible.

During the 1950's, when improved vacuum equipment became available, interest in the purification and microstructural control of alloy steels and superalloys increased considerably. By 1960, 150 million pounds of specialty steels and superalloys were being produced annually. Typical ingot sizes increased to 50-60 inches in diameter and weighed 50,000 to 80,000 pounds. During the 1960's, little was done to improve the basic process, although notable improvements in equipment, capacity, and capabilities occurred. Also important was the rebirth of interest in the Hopkins' process.

Furnace designs. - Four common types of arc-melting furnaces are used today: (1) the consumable-electrode arc melting furnace, (2) the nonconsumable- or inert-electrode arc-melting furnace, (3) the skull arc-melting furnace, and (4) the electroslag or electroflux-remelting furnace.

The most widely used design is the consumable-electrode arc-melting furnace. In this design, the electric arc is maintained between the molten metal in the crucible and a preformed bar (electrode) of the metallic raw material. As melting proceeds, the crucible is filled with metal by the transfer of liquid drops through the arc from the raw-material electrode. Figure 12 is a schematic drawing of a typical cold-crucible, consumable-electrode arc-melting furnace. This furnace is used extensively to produce ingots of various steels, superalloys, reactive metals, and refractory metals.

The inert- or nonconsumable-electrode arc-melting furnace, which is the second important design, produces an ingot microstructure that is characteristic of high-thermal-gradient materials. In this furnace, the electric arc is maintained between the molten metal in the crucible and a refractory nonconsumable electrode, such as thoriated tungsten. The electrode is neither consumed nor does it take part in any reaction; it only supplies the arc current. Thus, the process has been called inert-electrode arc melting. To minimize electrode vaporization, the melting

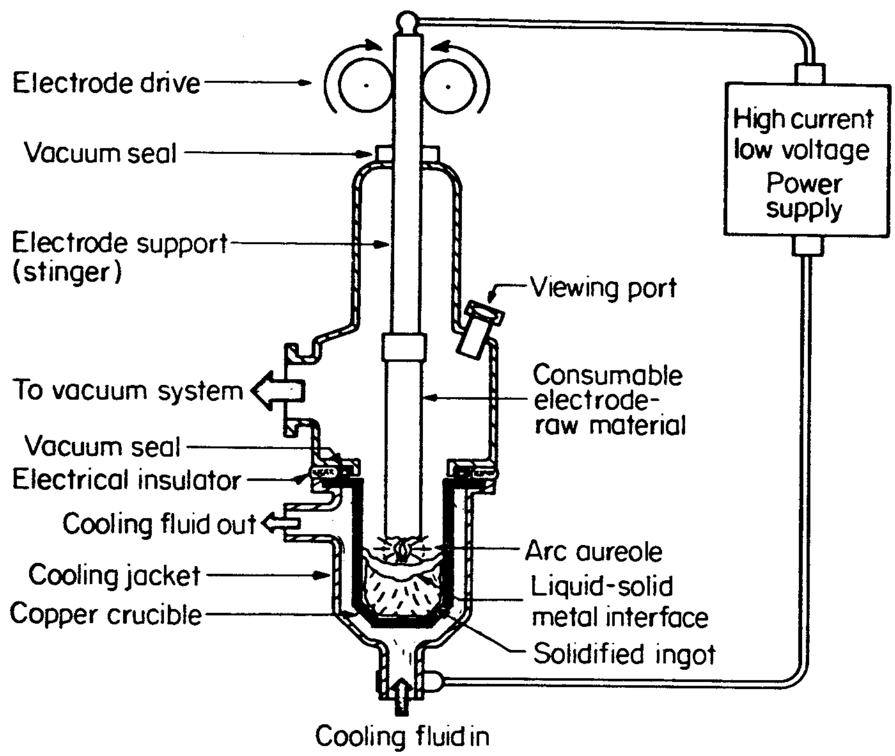


FIGURE 12. CONSUMABLE-ELECTRODE ARC-MELTING FURNACE DESIGN

(Courtesy S. J. Noesen, General Electric Company)

process is usually performed in an inert-gas atmosphere rather than in a vacuum. The raw materials, usually in the form of discrete particles, are supplied to the melting crucible by an auxiliary feeding device. This form of arc melting is particularly adaptable to the laboratory preparation of a large number of compositions in the form of small ingots, i.e., buttons that can be easily homogenized in a relatively short time. A typical design of this type of furnace is shown in figure 13.

The third arc-furnace design, the skull furnace, was developed to produce shaped castings. In this furnace, a given quantity of metal is rapidly melted in a chilled crucible and poured into a mold cavity to produce the shaped casting. A directional structure in ingots is not produced. The resulting castings are subject to defects as found in conventional casting, such as shrinkage holes, gas holes, and hot tears. Generally, the raw material is added as a consumable electrode, the chilled crucible is a relatively shallow vessel, and the entire process (including metal pouring) is carried out in a vacuum. After the metal has been poured, a solid crust or skull of the melted and cast metal remains in the chilled crucible. A schematic drawing of a typical skull arc-melting furnace is shown in figure 14.

The electroslag furnace is actually not an arc-melting furnace at all; it is included here because the equipment, the raw materials, and the resulting metallurgical products are similar to those of the vacuum-arc-melting process. The principal difference between the two processes lies in the method of heat generation. The electroflux technique does not utilize the intense heat of the electric arc as does normal arc melting. Instead, it depends upon the resistance heating (I^2R losses) of a molten flux which is interposed between the molten metallic pool (contained in a water-cooled copper crucible) and the consumable electrode. The melting current (AC or DC) passes down the electrode, through the molten flux (which has a higher electrical resistance), and on through the molten-pool and the solidified portion of the ingot. It then flows into the copper crucible and back to the power supply.

Heat generation: The heat utilized in the arc-melting process is generated by an electric arc between two metallic conductors. An arc is an intensely hot body of ionized elemental species through which a relatively high current is passing. At currents greater than 100 amperes this arc is characterized by a total voltage drop in the range of 20 to 45 volts.

In the most conventional system in use today (shown in figure 15), direct current is used and the solid electrode has negative polarity. This negative electrode is heated principally by the direct impingement of positive ions; the anode or molten pool receives its greatest amount of heat by conduction from the plasma in the positive column. The arc plasma column is heated by the kinetic energy gained by electrons in the cathode fall and by ohmic heating in the collision-dominated region.

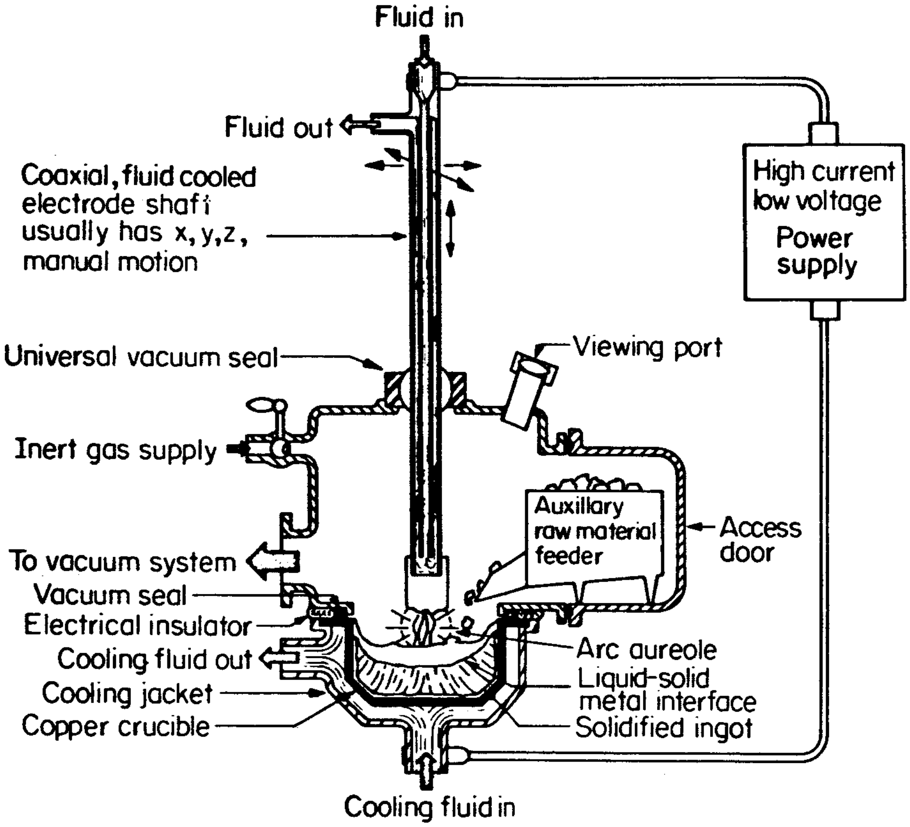


FIGURE 13. NONCONSUMABLE-ELECTRODE ARC-MELTING FURNACE DESIGN

(Courtesy S. J. Noesen, General Electric Company)

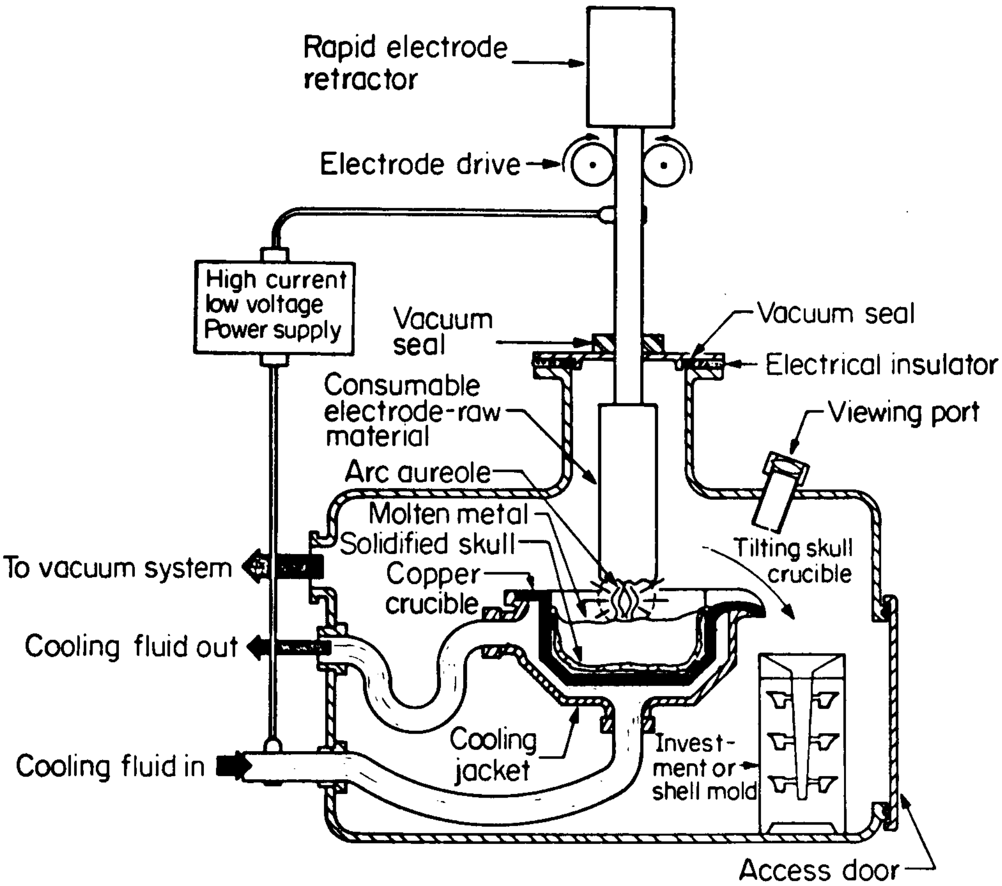


FIGURE 14. SKULL ARC-MELTING FURNACE DESIGN

(Courtesy S. J. Noesen, General Electric Company)

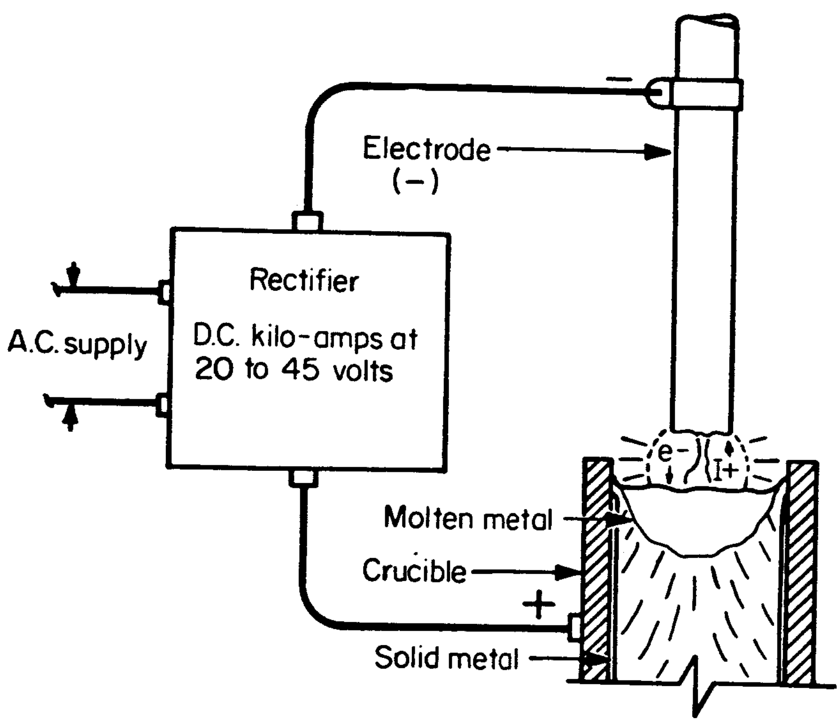


FIGURE 15. CONVERSION OF ELECTRICAL TO THERMAL ENERGY IN VACUUM ARC MELTING

The voltage drop of the arc depends on the emission characteristics of the cathode, the plasma electron density, the length of arc, and very slightly on the arc current. Significant physical properties of the materials include ionization potentials, work function (for cathode) vaporization point, thermal conductivity, and heat of vaporization. The arc plasma is ionized partly by the energetic cathode fall electrons, and partly by thermal processes. The amount of heat generated is related directly to the arc current. The currents that are commonly employed in arc melting are in the kilo-amperage range. Direct resistance heating of the electrode is a secondary heating mechanism which is of little importance in terms of the quantity of heat generated.

The power required to arc-melt depends directly on the melting point, the specific heat, the heat of fusion, and the thermal conductivity of the metal or alloy under consideration. Once the melting power has been established for a given crucible size and metal, several additional measures can be used to affect the electrode melt-off rate, which controls the rate of the process. A maximum electrode melt-off rate is desired for high production rates with the attendant minimization of impurity removal; a minimum melt-off rate, on the other hand, yields the maximum molten-metal residence time which in turn results in maximum vacuum purification.

The electrode melt-off rate can be altered (independent of the primary arc-melting power) in the following ways:

(1) By varying the electrode diameter (Larger diameter electrodes yield lower melt rates because of increased current and heat-carrying capacity.)

(2) By increasing the density of the electrode (Lower melt rates are obtained by lowering the electrode's resistivity and, thus, its internal heat generation by I^2R losses. This method is very useful when utilizing pressed-powder electrodes as for casting refractory and reactive metals, but it is not applicable to cast electrodes.)

(3) By adding gaseous elements which either change the voltage characteristics of the arc or redistribute the heat dissipation between the anode and cathode surfaces (Diatomic gases, such as hydrogen, are effective.)

(4) By decreasing the ratio of crucible diameter to electrode diameter (A decrease in the amount of radiant energy received by the electrode is obtained. This results in a decrease in the melt-off rate for a given electrode size. Very striking effects are obtained, particularly in the case of the highly refractory metals.)

(5) By adding a material which is a good thermionic emitter, i.e., one with a low work function, to the consumable electrode (An appreciable decrease in the melt-off rate can be achieved. Very small quantities of both elements and compounds have been used successfully. Yttrium and thorium oxide have been used successfully to lower the electrode melt-off rate and have resulted in ingots having residual impurities which are almost undetectable.).

Electrical power supplies: Direct-current supplies are used for the majority of modern arc furnaces. The specific power levels and combinations of melting voltage and amperage vary somewhat with the specific objective of the melting operation. In addition, melting voltage is characteristic of the material being melted and can only be varied between specific limits to achieve special effects, e.g., improved ingot side walls are obtained by operating with the highest voltages specified for a given element.

The electrical power supply for successful arc melting must have high current capacity and be able to maintain a relatively constant current independent of the load and the changing impedance of the arc. In the early commercial installation, dc welding generators in parallel were commonly employed, but today new installations utilize solid-state rectification to obtain the desired direct current. Selenium and germanium rectifier banks were also used with some success in the past. Today, high-temperature silicon rectifiers are the most acceptable for this application. An open circuit voltage of 80 to 90 volts is required for these units (1) to start the arc, and (2) to maintain the electrical discharge throughout the melt.

The arc is started by bringing the electrode into direct contact with some raw material placed in the melting crucible. At the point of contact, the I^2R losses quickly generate sufficient heat to cause fusion and the direct short is broken in a manner similar to the melting of a fuse link. The arc is thus initiated without the benefit of a high-voltage spark, and an open circuit voltage of only 100 volts or less is required. In most cases, an open circuit voltage about double the normal operating voltage is necessary to insure continuous arc operation during discharge fluctuations. Discharge fluctuations are often caused by density and compositional inhomogeneities of the electrode.

Arc-length control: Apart from the supply of power, the major electrical installation is usually the arc-length control. Although the melting operation may be controlled by an observer viewing the arc optically, some automatic method of control is normally employed. Automatic control, more convenient and consistent, frees the operator to concentrate on the other factors involved in the arc-melting process.

Visual observation of the arc is important, however, and provision for this is usually made even when automatic devices are included. The beginning and end of the melting operation are very important and must be closely watched – the beginning, to see that the arc is struck satisfactorily between the metal plug and the tip of the electrode, and the end (when the current is reduced to allow the ingot top to solidify fairly slowly) to reduce shrinkage cavities. During normal operation, no process indicator can signal unusual conditions as quickly nor can any built-in safety system be so versatile as a skilled observer. It is usual for the observer to be separated from the furnace behind blast walls; the arc is observed by means of a remote television camera or a periscope arranged to look down the sides of the electrode. Since it is often advantageous to be able to see both sides of the electrode, two-mirror systems are sometimes employed.

Electrode arc-length control and drive systems are areas of vacuum arc-furnace technology that have received much attention in recent years and in which there is much controversy among furnace manufacturers. Several different designs are available. Many drive systems are hydraulic and control systems are solid-state. Sometimes the drive system that feeds the electrode to the arc is assisted by a stinger rod which is introduced into the furnace chamber through dynamic vacuum seals. In this case, clamping beads are used to connect the consumable electrode to the stinger rod. A common control system depends on arc pulses that occur in the arc voltage during melting. This system operates on the principle or premise that the frequency and magnitude of positive arc pulses are a direct function of the arc length and hence the molten-metal-transfer rate.

One newer design employs the "phantom" (transient, millisecond-duration) short-circuit conditions within the arc zone as a control reference. This design is based upon the relationship that appears to exist between the arc-length dimension and the phantom short-circuit characteristics. Such a design is said to regulate accurately the arc length regardless of arc-voltage, arc-current, or vacuum-pressure variations.

Crucibles: Broadly speaking, a vacuum-arc-melting crucible is essentially a copper tube, which can be fabricated by extruding, rolling, or welding copper plate, or by electrodepositing seamless copper. Flanges on crucibles are commonly made of low-carbon steel, stainless steel, or copper. Crucibles are often tapered slightly to facilitate stripping.

The crucible serves four distinct functions:

(1) It holds liquid metal during progressive solidification into ingot form.

(2) It transfers heat through the wall and bottom to the surrounding water jacket.

(3) It transmits electrical power through the top flange and tube to the bottom cover and thus establishes an electrical path to the electrode.

(4) It serves as an evacuated vessel capable of holding reduced pressures or atmospheres for the melting operation.

A variety of crucible problems may occur in the melt shop. One major problem is mechanical, thermal, or metallurgical damage caused by hung or stuck ingots.

Another problem is the curved or banana-shaped crucible caused by poor crucible handling or by mechanically abusing the crucible while attempting to remove an ingot; still another problem is cracks in the tube wall as a result of improper welding.

Vacuum-arc-melting operations. - Many vacuum-arc-melting facilities exist in the United States. In many cases, the designs of these facilities differ because of technological changes and the different needs of the various metal producers. A broad classification of facility designs may be made according to furnace manufacturers. The majority of commercial furnaces have been designed and installed by three manufacturers - Lectromelt Furnace Division of Pecor Corporation, the Consarc Corporation, and Leybold-Heraeus, Inc. A few facilities were designed and constructed by the metals producers themselves or contracted by them to other firms.

Most newer furnace designs incorporate dual melting station arrangements. This design makes it possible to make preparations for melting at one station while melting is being carried out in the other. Fast turnaround times (from arc-out to arc-strike in the alternate melt station) is a feature of this design.

Various vacuum-arc-melting facility designs are shown in figures 16, 17, and 18. Most leading superalloy producers possess a series of consumable-electrode vacuum-arc-melting furnaces usually of different designs.

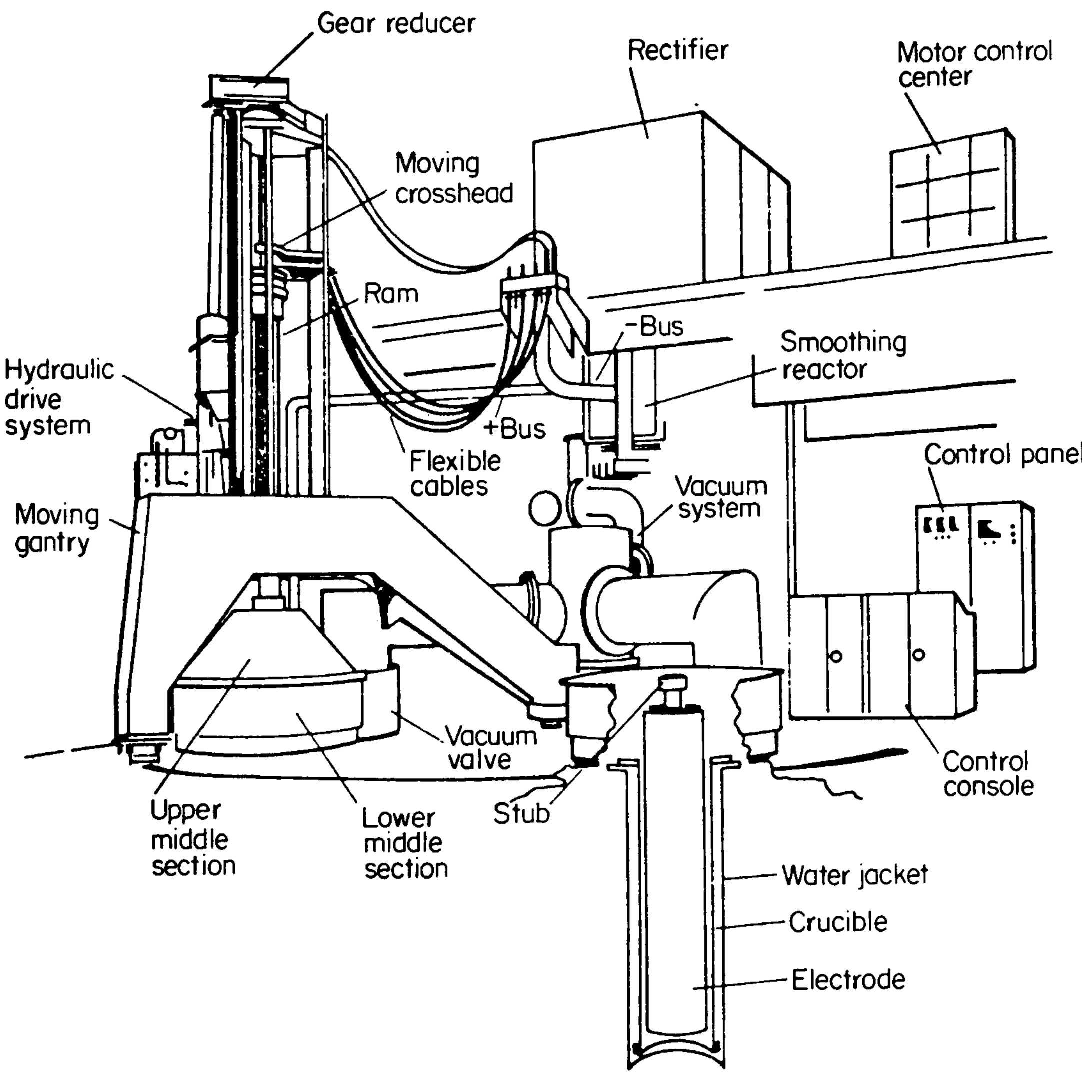


FIGURE 16. CONSUMABLE-ELECTRODE VACUUM-ARC-MELTING FURNACE

(Courtesy Pecor Corporation)

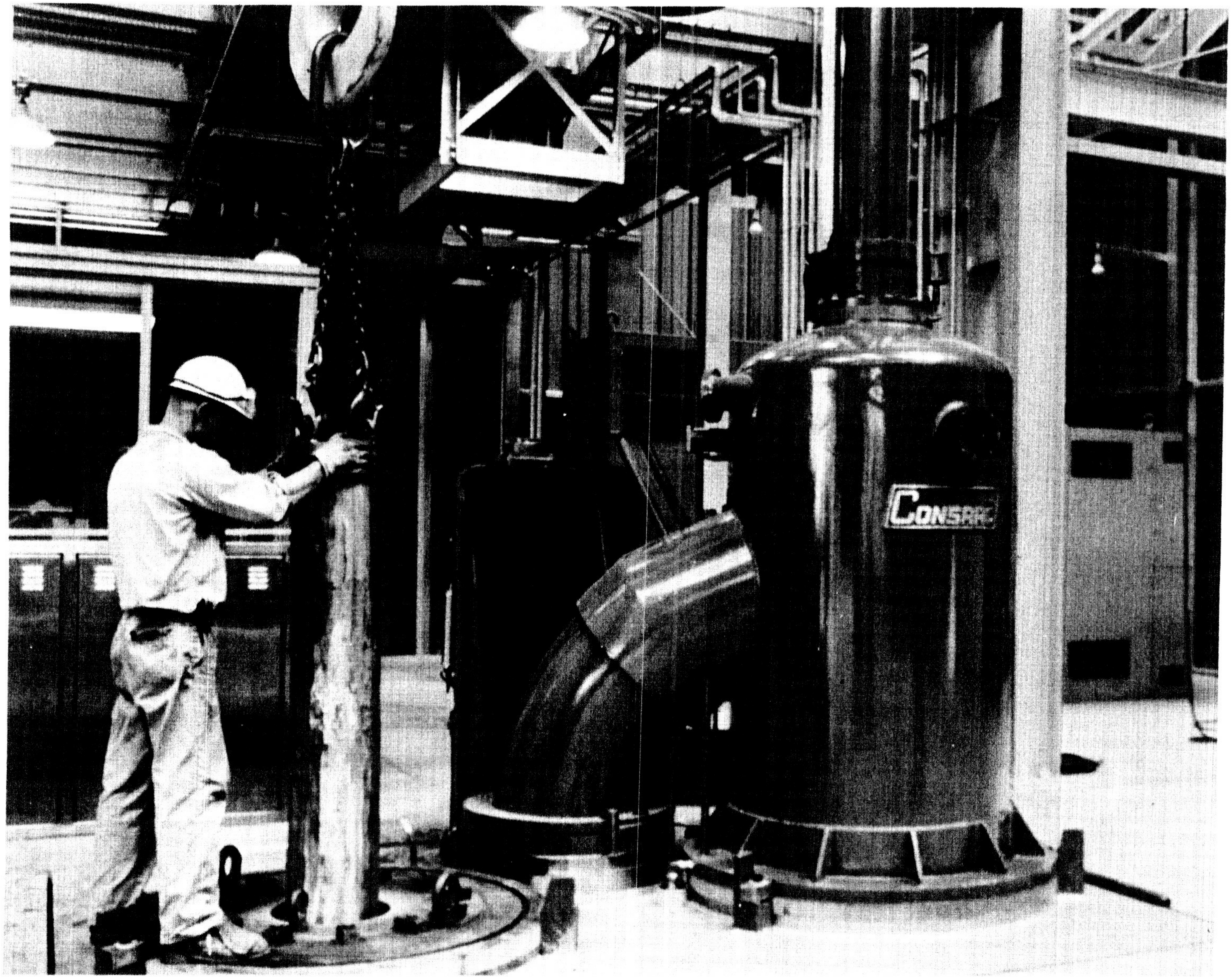


FIGURE 17. LOADING AN ELECTRODE AT ONE STATION OF A VACUUM-ARC-MELTING FURNACE

(Courtesy Consarc Corporation)

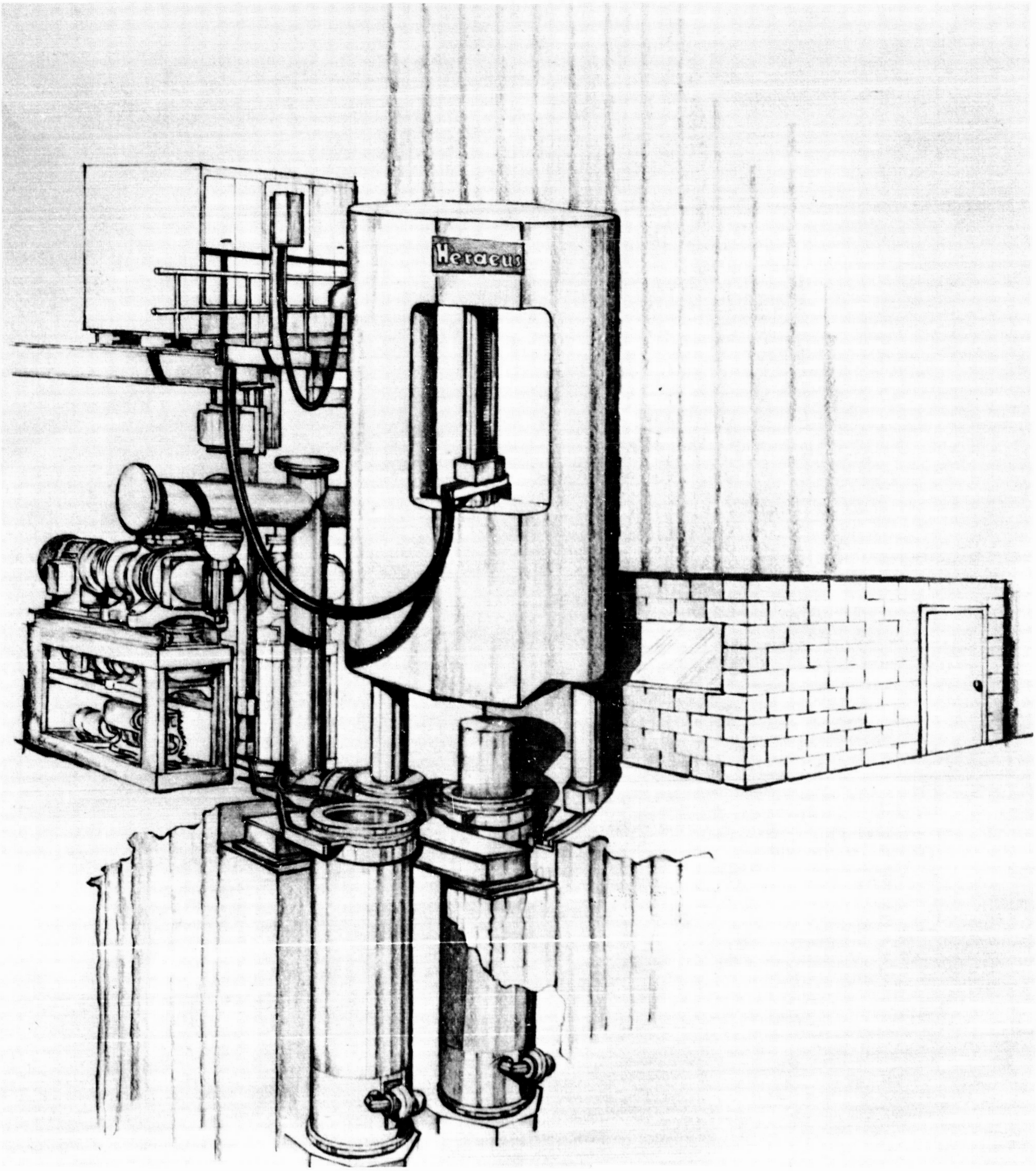


FIGURE 18. CONSUMABLE-ELECTRODE VACUUM-ARC-MELTING FURNACE INSTALLATION FOR INGOTS UP TO 45-INCH DIAMETER

(Courtesy of Leybold-Heraeus, Inc.)

Electroslag Remelting

The development of electroslag remelting. - In 1940, R. K. Hopkins was granted a patent on a technique called "The Kellogg Electric Ingot Process". This was the first commercial application of consumable electroslag remelting (ESR) in the United States. The original Hopkins Process, as it was later called, utilized tubular electrodes which were continuously formed from a coil of strip with the proper base composition(35). For example, iron-base alloys were prepared using electrodes made from AISI 1010 strip, and nickel strip was used for the preparation of nickel-base alloys. Granular alloying additions were made through the tubular electrodes at a rate necessary to produce the desired final composition. Fluxes needed to form the desired slag blanket were also added as melting proceeded.

The tubular-electrode concept was successfully used for many years, with improvements being made from time to time. This process, however, had one serious shortcoming. Users periodically found strip inclusions in the finished products. These defects were ultimately traced to fragments of the tubular electrode which were trapped in the solidifying metal. Certain modifications of melting techniques were instrumental in minimizing the strip inclusions; however, they were never completely eliminated. Thus, in the early 1950's, solid electrodes were substituted for the tubular electrodes previously used, and the addition of granular alloying elements was abandoned in favor of the use of the solid electrode of approximately of the desired composition.

In early work with the Hopkins process, most of the steels produced were stainless Type 300 and Type 400 grades. During World War II, hundreds of tons of steel were made by this process, most of which were high-speed tool-steel grades supplied in the forged, rolled, and as-cast conditions. Many special grades were also made, but most of the tonnage of the stainless types was confined to an alloy developed for welding rods used for the welding of armor plate.

In 1947, the first high-temperature alloy, 16-25-6 (iron, 16 chromium, 25 nickel, 6 molybdenum) was melted by the electroslag process. At that time, this alloy was being used in the turbine wheel of the J-33 jet engine. As a result of favorable experience with this alloy, other high-temperature materials were investigated, and in a relatively short time it was found that practically any of the high-temperature alloys could be produced by the ESR process, and with the same success as with the 16-25-6 alloy.

Encouraged by the findings of some experimental studies, Firth Sterling acquired all rights to the Hopkins Process and the equipment from the M. W. Kellogg Company in 1959. Commercial producing and marketing of various grades of high-quality steels produced by the

Hopkins Process commenced at Sterling the same year. Sterling licensees now include Carpenter Steel, Union Electric, and Union Carbide, as well as Lectromelt (an exclusive licensee for Hopkins Process equipment in the U. S.) and Heraeus-Engelhard (an exclusive licensee for ESR equipment outside the U. S.). At the present time, only Firth Sterling and Union Carbide's Materials Systems Division are now in commercial production.

In 1964, the British Iron and Steel Research Association established the Electroslag Refining Technology Group[36]. Services offered by ESRT include contract melting, evaluation trials, investigations of slags, and general consulting. In the U. S., Consarc Inc., the U. S. Licensee of ESRT, has been selling an electroslag remelting unit since 1966.

More recently the Electroslag Institute has been established[37]. The prime objective of ESI has been to hasten the scaling up and commercialization of ESR technology. The industry members of ESI share the funding of the Institute and receive in return improvements in the technology as a result of Institute research and development. Any developments, improvements, or patent rights acquired by the Institute are extended to all members; however, proprietary information acquired by the members need not be divulged.

Process operation.

Functions of the slag: The heart of the electroslag process and the feature distinguishing it from other consumable melting techniques is the use of a molten slag. Under proper controls the slag performs four prime functions:

- The slag is resistively heated to accomplish the melting of a submerged consumable electrode.
- It protects the molten metal from contamination by the furnace atmosphere.
- It provides a cleansing action to the molten metal.
- It freezes on the walls of the water-cooled copper mold and isolates the solidifying ingot from the mold.

Each of these functions is discussed in detail below.

The ESR process is essentially an arcless consumable melting process in which the heat is derived from the electrical resistance heating of the molten slag. During the melting operation the electrode is immersed in the slag and the energy is dissipated in the form of current flowing through the ionized slag. Although the melting point of the slag is typically lower than that of the material to be melted[38], the temperature of the molten slag is normally much higher than the melting point of the electrode

material. Thus, the slag bath remains molten while the electrode material is slowly melted away by immersion in the slag bath. Gravitational forces and the wetting action of the slag result in the continuous melting of the electrode and the formation of a fine stream of small droplets. These droplets transfer through the slag to the molten-metal pool on the top of the ingot.

The use of a molten slag as a heat source has several inherent advantages. The temperature surrounding the electrode, being relatively stable, results in uniform and predictable melting rates in electroslag furnaces. A second advantage of slag heating is that the temperature across the cross section of the ingot is fairly uniform and subject to control. The melting rates can be controlled to give shallow and relatively flat molten pools under the slag. This increases the tendency for axial solidification of the ingot, thus, decreasing the tendency for microsegregation and promoting flotation of light-weight nonmetallic inclusions. A third factor associated with the use of the slag heating is a decreasing tendency toward microporosity and piping. This is apparently related to the hot top action of the molten slag as well as to the directional nature of solidification.

The protection from the furnace atmosphere provided by the presence of molten slag atop the solidifying ingot has, for many materials, provided the opportunity to electroslag-melt in an air atmosphere rather than under vacuum. Air electroslag melting has been routinely used for many steels and nickel-base superalloys; however, the melting of highly reactive materials such as titanium or of materials containing significant amounts of titanium or aluminum is generally conducted in vacuum atmospheres.

The purifying or cleansing action provided by the slag is dependent primarily upon the chemical composition of the slag. Calcium fluoride is a good choice of slag for many applications. It can, however, be improved by additions of up to 30-percent CaO for sulphur and phosphorus removal or of alumina for increased resistance and higher melting points, and for removal of silica inclusions(39). The density of the molten metal and its wettability by the molten slag control the size of the droplets of molten metal which move through the slag. It is during this period of transference through the slag that the droplets may be chemically purified by the action of the slag. The purifying action is thus enhanced by the formation of droplets of minimum size, that is, by maximizing the surface-to-volume ratio of the droplets. In addition, low-melting metals, gaseous and nonmetallic inclusions may be completely or partially removed from the remelted metal. Low-boiling-point materials are removed by vaporization, and the gases, by virtue of their higher solubility in the slag than in the metal, are absorbed in the slag. Low-density, nonmetallic inclusions float up into the molten slag where they are permanently held.

As solidification proceeds, the slag freezes on the surface of the water-cooled copper mold. The frozen slag layer performs two functions. First, in protecting the solidifying ingot from the mold, it eliminates cold

shuts and promotes smooth ingots surfaces. Second, as a thermal insulator it tends to resist axial solidification of the ingots.

Design of the basic Hopkins furnace: Figure 19 is a schematic of the Hopkins Process showing the principal operating features[35]. During melting the electrode is immersed in the molten slag; the conduction path during melting is electrode → ionized slag → molten-metal pool → solidified ingot → copper mold. (Electroslag melting can also be operated on alternating current.) The solidified ingot is contained in a water-cooled copper mold. As solidification proceeds, a thin layer of slag solidifies against the mold wall, and the ingot freezes within the solidified flux skin. Flux is added at the start of melting and is continually fed into the mold during the process. Small amounts of alloying additions may be added to control final ingot compositions.

Electrode motion may be controlled either by a drive wheel mounted on the shaft of a motor or by a slide operated through a motorized-pulley arrangement.

Melting procedures: The most widely accepted method of starting the electroslag operation utilizes powdered flux. A starting plug of the same composition as the electrode to be melted is placed on top of the water-cooled copper stool within the copper mold. The electrode is lowered into the mold and placed in contact with the chips or turnings of the material that is to be melted on top of the plug, and a predetermined weight of the powdered flux covers the plug and lower end of the electrode. A minute or two after power is applied, the flux becomes molten, and the cycle is continuous until the desired amount of ingot has been melted. An alternative starting procedure reported by AEI-Birlec[39] consists of pouring premelted slag into the empty mold. Power is applied to the immersed electrode and the molten slag is resistively heated, thus initiating melting of the electrode. The use of premelted slag tends to eliminate porosity and roughness at the bottom of the ingot and thereby increases the yield of good material.

Several interdependent variables affect the metallurgical quality of the material formed by electroslag melting. Among these are voltage, current, electrode feed rate, electrode cross section, electrical and thermal conductivity of the slag and depth of the molten slag. These factors control primarily the heat-transfer characteristics of the system, which in turn control the grain structure (orientation) of the cast ingot. The heat transfer characteristics of the system are displayed in the shape of the molten-metal pool on top of the solidifying ingot. Shallow pools (approaching a planar-growth front) result in axially aligned columnar grains, while deeply cupped molten pools resulted in radially oriented grains.

Ingot characteristics: Characteristics that reportedly contribute to the metallurgical quality of electroslag-melted ingots are:

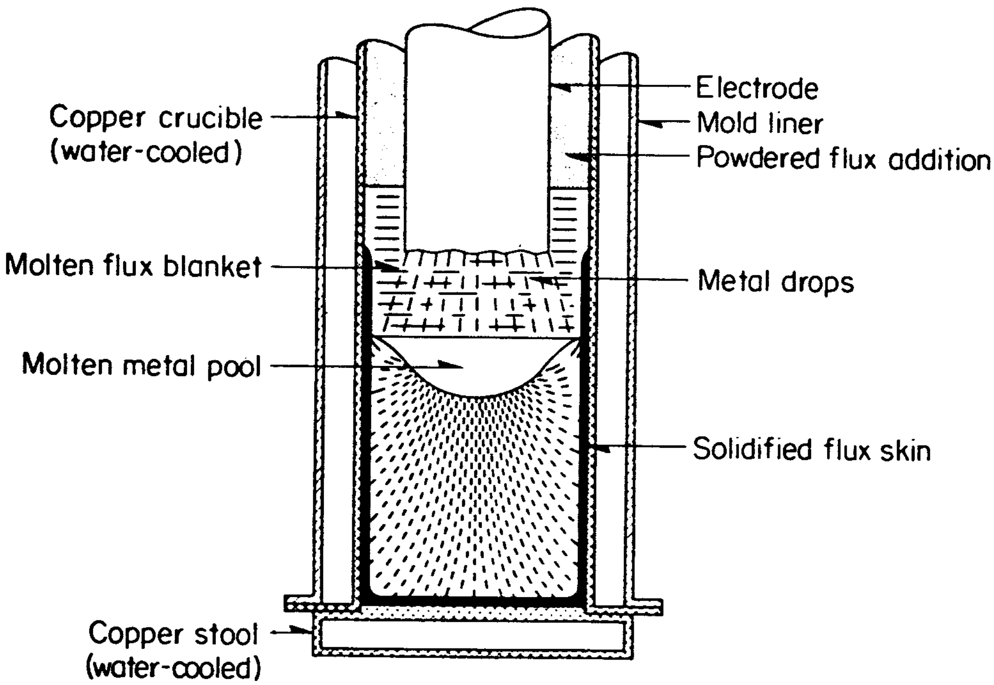


FIGURE 19. BASIC FEATURES OF THE HOPKINS ELECTROSLAG MELTING PROCESS[35]

- Minimized macro- and microsegregation
- Minimized porosity pipe and microshrinkage
- Low nonmetallic-inclusions counts
- Good surface finishes
- Good fabricability.

Careful control of melting conditions must be maintained to achieve these characteristics.

Segregation is a problem common to all alloy-casting operations; however, consumable melting techniques have shown a capability to decrease both macroscopic and microscopic segregation from that observed in cast ingots, especially for large-diameter ingots. This difference is related primarily to the local freezing rate at the liquid-solid interface which controls the secondary dendrite arm spacing. Large dendrite arm spacings result in fewer arms for the rejection of solute thereby resulting in a greater amount of solute rejection per dendrite arm. This in turn, results in larger pools of solute-rich materials in the solidified ingot. Thus the degree of segregation is minimized by promoting small interdendritic arm spacings. It has been established by many investigators that high local freezing rates promote small interdendritic spacing and thus decrease the degree of segregation[40]. For consumable melting techniques such as ESR and VAR the local freezing rate is inversely proportional to the rate at which the electrode is melted, and therefore the dendrite arm spacing (or the degree of segregation) increases as the melting rate increases.

The electroslag-melting process also provides a potential for decreased pipe and microshrinkage porosity. The amount of pipe present in an electroslag ingot is reduced by two factors. The directional nature of the solidification, experienced under proper process control, as well as the hot-top action provided by the resistively heated slag tend to eliminate central shrinkage pipe. Microshrinkage is typically formed at interdendrite positions as a result of insufficient feeding of solidification shrinkage in this area by the molten pool. The highly axial nature of freezing in this process allows for more efficient feeding of interdendritic shrinkage from the molten metal pool.

The slag can react with the melt to provide a reduction in nonmetallic inclusions. However, with the present state of the art of electroslag melting, the process has frequently not been successful in removing all microscopic oxide (Type "D") inclusions. This problem probably can be overcome for most materials when appropriate slags are developed.

The excellent ingot surfaces typically produced by electroslag melting is a direct result of the formation of a thin solidified-slag layer on the

inside surface of the water-cooled copper mold. The presence of this layer tends to reduce the formation of cold shuts and rough surfaces.

The grain morphology of electroslag-melted ingots was discussed earlier. In addition to the advantages already mentioned of the axially oriented grains resulting from the process, these grains are desirable for reasons of improved ingot fabricability. ESR ingots typically exhibit improved transverse ductility that frequently results in improved hot-work ability for ESR materials.

Power requirements: Because the slag is heated by electrical resistance, the power requirements for ESR are very flexible. ESR can be operated by either ac or dc or by a combination of both. With ac melting there is further choice of single phase or polyphase melting. The power level required can be altered by changes in slag composition and slag thickness. It can also be adjusted by techniques such as reciprocation of the mold which can enable reduced power and, hence, reduced temperature to be used in complex situations[(41)].

During recent years, the relative merits of ac vs dc power supplies for ESR melting have been hotly debated. In this country, Firth Sterling and Union Electric are using dc while the new Consarc continuous furnaces at Union Carbide's Materials Systems Division are ac. Most overseas furnaces use ac. Kobe Steel claims improved desulfurization with ac and Birlec Ltd.'s ten installations use ac. After 150-160 experimental heats to evaluate ac versus dc power supply, Mellon Institute tends to favor ac[(37)]. Because of the similar power requirements, much of the experimental work done on electroslag remelting has been accomplished in converted vacuum arc furnaces. Experiments conducted in these furnaces use dc power supplies.

A second contested point is the use of three-phase vs single-phase current. Work at Consarc (Europe) has established a preference for single-phase operation for metallurgical reasons[(42)]. With three-phase operation, the uncontrolled bath motion can cause considerable segregation which in general is detrimental to the perifery of the ingot. If melt stirring is required for a specific application, their preference is to use auxiliary stirring coils.

Electrode characteristics: The electrodes used in electroslag remelting can be cast rolled, or forged. For making variously shaped ingots, electrodes of the ingot shape are usually used; however, this is not a strict necessity. Slab or tubular ingots have in the past been melted from a series of solid cylindrical ingots. Even the need to have a consumable electrode can be avoided in ESR. The charge material can be added in the form of scrap, powder, or even liquid metal and a nonconsumable electrode is used to heat the slag.

In the United States the ratio of the diameter of the consumable electrode to that of the mold is normally 0.6 to 0.7[(38)]. Larger diameter

electrodes may result in problems of arcing between the copper mold and the electrode. One commercial process uses strip electrodes for casting 4 in. x 4 in. square cross-section ingots (continuous casting).

Commercial furnaces. – The four companies currently engaged in ESR production in the United States are listed in table 9 with a few basic facts about the type of furnace employed. ESR furnaces used by these producers have been supplied by Firth Sterling, Consarc, and Arcos.

TABLE 9. – DESIGN OF COMMERCIAL ESR UNITS IN THE UNITED STATES[37]

	Design	No. of Units	Amperes	Max Ingot Size, in.[a]
Firth Sterling	F-S	3	12,500	16
		1	15,000	20
Cybermetals	Arcos	1	--	4 x 4
Union Carbide	Consarc	1	17,500	30
Stellite Works		1	25,000	30
Union Electric	F-S/Heraeus	1	--	30

(a) Only cylindrical shapes are listed. A number of installations produce slabs and billets also.

Application of electroslag remelting to superalloys.

Justification for projected and current use: Current requirements of commercial aircraft builders for larger more economical engines have placed new demands on the superalloy producers. In addition to the alloy development required by the higher operating temperatures of larger high-thrust engines, the producers have been required to supply larger billets of the superalloys for the production of more massive shapes.

The initial approach to the production of larger billets was to increase the diameter of the vacuum-arc-remelted ingots. Large vacuum-arc-remelted ingots, however, have the conspicuous shortcoming that the degree of segregation in the arc-melted ingots increases substantially with increasing diameters. In most instances neither homogenization nor hot reduction is successful in eliminating this highly segregated condition. To reduce alloy segregation in VAR production, the technique typically employed is to decrease the melt rate by reducing the power input to the furnace. However, as the power input is decreased beyond a certain critical level the ingot surfaces become quite rough and in some cases, cold shuts are evident. Rougher surfaces tend to hinder subsequent fabrication operations such as rolling or forging, and costly prior preparation of ingots is required. In highly complex alloys where large amounts of solute are rejected during solidification, a practical limit of 24-in. diameter ingots are available with current technology.

Because of the tendency for reduced segregation in ESR-produced materials, the electroslag melting of superalloys may have significant application to the production of larger-diameter ingots with minimal segregation.

Other reasons for selecting the electroslag-melting technique for the production of various superalloy materials may depend upon a variety of circumstances. Reference is made to the ingot characteristics discussed in a previous section. When these characteristics for a specific superalloy material represent significant improvements over those experienced for VAR or induction-melted materials or when economic advantages exist, ESR may be used for the production of that material. Obviously, the use of ESR for such materials will depend primarily on the success currently obtained with VAR or induction-melting techniques.

Current commercial and experimental applications: Unfortunately, the majority of work conducted in the United States on electroslag melting has been veiled in a cloak of secrecy. Several producers are currently involved in experimental studies on electroslag melting, but they have been extremely reluctant to discuss processing conditions and especially slag compositions. One detailed experimental study, however, has been conducted by Mellon Institute under the sponsorship of the U. S. Air Force[43]. The primary objective of this program was to develop a manufacturing process for the electroslag melting of several specific alloys including 18-percent nickel maraging steel, René 41, Inco 713C, and Udimet 700. Work reported to date on the last three alloys is summarized here as representing problems encountered in the electroslag melting of superalloys.

René 41 is a hot-workable nickel-base superalloy. Four-inch diameter, dc-straight-polarity melted ingots of René 41 were initially made in a laboratory furnace. The composition of the flux found to be most successful for this system is as follows: 30-percent CaF_2, 40-percent Al_2O_3, 17-percent CaO, and 13-percent MgO. Chemical analysis showed that the recovery of titanium and aluminum, the two most reactive elements in this alloy, was greater than 95 percent in practically all cases. These 4-inch diameter ingots displayed excellent hot workability as shown by the results of hammer forging these ingots into 1-in. thick plate. The subsequent scale-up of René 41 melting to 7-inch diameter ingot in a production facility was accomplished with similar results. Recoveries of aluminum and titanium for this ingot were again 95 percent higher, and the ingot was directly hot-rolled in the as-cast condition on a reversing mill to 1-in. thick plate. Conversion was accomplished in 14 passes with a single reheat following the fourth pass. Mechanical-property specimens cut from these rolled plates showed improved room-temperature tensile properties over those of specimens cut from the electrode material. The material showed higher room-temperature yield strengths with very good ductility. At 1700 C the ESR material showed slightly lower strength levels, however, significant increases were observed in both the ductility and reduction in area.

Inco 713C is commonly used in the as-cast condition, partially because of its poor hot workability. The primary objective of studies with this alloy was to determine if ESR increased the hot workability of the alloy. Four-inch diameter ESR ingots were made in a laboratory furnace with the production of sound ingots. Chemical analysis showed recoveries of aluminum and titanium at better than 95 and 90 percent, respectively. Hot working of these ingots was considered partially successful. Direct hot-press forging was terminated at 50-to 75-percent reduction when severe cracking developed. One-in. plate was directly hot-rolled from a 4-in. diameter ingot in six passes without reheat. Severe cracking developed on the surface and edges of the plate; however, the cracking was in general shallow, and confined mostly from 1/8 to 3/16 inch from the plate surface. The estimated recovery of usable material was 60 percent, and ample material was available to conduct several mechanical-property tests. These hot-working results represent an improvement over Inco 713C produced by other melting techniques. Room-temperature and 1700-F mechanical properties were in general superior to those of vacuum-melted and vacuum-cast 713C alloy.

Nickel-base superalloy, Udimet 700, generally shows marginal hot workability. Four-in. diameter ESR ingots produced by dc straight polarity again have shown titanium and aluminum recoveries greater than 95 and 90 percent, respectively. They have also demonstrated suitable hot workability under conditions of direct hot rolling of 4-in. ingots to 1-in. thick plate. Room-temperature and 1700-F mechanical properties, similar to those of samples cut from the electrode materials, showed a slightly lower yield strength at room temperature and a slightly higher yield strength at 1700 F. Ductilities were greater for the ESR material at room temperature and slightly less than that of the electrode samples at 1700 F.

These studies at Mellon Institute[(43)] have shown that sound ingots of the nickel-base superalloys can be very simply melted by the ESR technique. These ingots have demonstrated hot workabilities as good or superior to those obtained with ingots cast by more conventional techniques. The mechanical properties of the ESR materials are satisfactory and in some cases superior to similar properties generated from the respective electrode materials.

Union Carbide's Materials Systems Division is currently commercially producing Hastelloy Alloys X, B, C, and C-276 as well as Haynes Alloy 25 by the electroslag process. This group has also reported[(41)] experimental studies on the application of ESR to Hastelloy Alloys F and B and to Alloys HS-31 and HS-6b. All of these alloys suffer from segregation and ingot defects in air-melted-and-cast ingots. In addition, the two cobalt-base alloys are not readily hot-worked as air-melted ingots. VAR and ESR techniques were applied to all four alloys with the production of 6-in.-diameter ingots. An ac electroslag furnace was used with CaF_2-CaO-Al_2O_3 slags. ESR has a greater effect than VAR in improving the cleanliness of the two cobalt-base alloys and produced Hastelloy-F ingots with significantly lower inclusion counts than those of VAR ingots while little or no difference in inclusion count was noted for Hastelloy-B.

Except for Hastelloy-B, ESR improved the hot ductility and forgeability of all alloys over that observed in VAR ingots. The evaluation of ingot chemistry showed that ESR had a tendency to remove highly oxidizable elements and did not remove hydrogen to the extent noted for VAR.

The Hopkins Process has been used extensively for the commercial production of the iron-nickel-base alloys 16-25-6 and A-286[38]. Firth Sterling has also reported experimental work on the nickel-base alloys Waspaloy B, Inconel 625, and Alloy 718[40].

This discussion of superalloy melting by ESR is intended not as a complete listing of all work in this area, but, rather, as an indication of some of the superalloy materials that can be produced by the electroslag process.

Electron Beam Melting

During the last decade electron beam (EB) melting has made the transition from being a laboratory curiosity to being a standard melting technique for many materials. The primary applications of EB melting have centered on the production of high-purity refractory metals, though, some current work has been directed toward the melting and continuous casting of steel. Only minimum work has been accomplished on the EB melting of superalloys. However, it appears that this technique may have certain advantages for superalloy production in the future and so is included in the discussion of melting techniques for superalloys.

The basic principal of the EB process is very simple. A heated cathode in a high-vacuum environment thermionically emits electrons that are accelerated through a voltage drop. The electron beam, focused by electric and magnetic fields, bombards the metal to be melted. Upon collision with the metal the electrons lose kinetic energy that is primarily dissipated as the heat that melts the charge material.

Development of electron beam melting. – Although the potential for using electron beams as a heat source for melting has been recognized for over 60 years[45], the basic developments necessary for commercial utilization of this technique have been accomplished primarily within the last decade. H. R. Smith, of Airco-Temescal has noted three primary reasons for this delayed development[46].

- Adequately pumped high-vacuum systems were not routinely available.
- Power supplies for generating and controlling electron beams were not available on a large scale and, even for small work, they were generally unreliable.

- Electron gun designs were based on vacuum-tube designs and were not rugged enough to withstand pressure excursions and ion bombardment found in processing operation.

Recent advances in these three areas have resulted in the current emphasis placed on electron beam melting. The ability to produce high-purity refractory-metal ingots with improved ductility (and thus better fabricability) has resulted in almost 100-percent conversion to EB melting for these metals[46]. The development of the electron-beam hearth-melting furnace during the last several years represents a significant advance because of the versatility afforded by this process.

Process operation.

Electron guns: Several types of electron guns are in general use for electron beam melting; however, only two are being used for research and development as well as for production applications. These are the Pierce-type gun and the transverse-field linear gun.

The well-known, axially symmetric Pierce-type gun shown in figure 20 has continued to prove popular for laboratory-scale equipment (many variations of it have been described in the literature) since development work is not required to construct one. In this gun[47], a dynamic seal between the gun chamber and the melting chamber keeps the melting chamber free of electrical fields. A low-conductance aperture between the two chambers allows the passage of the accelerated electrons and at the same time makes possible a pressure differential between the gun and melting chambers. A lower pressure thus can be maintained in the gun chamber to greatly reduce the possibility of accidental glow discharges that occur during large gas bursts from the melt and that generally reduce ingot quality. This design also provides good protection against splashes and vapor deposition on the cathode and provides a long distance between the electron source and the melt. It also produces a fine, easily focused spot and lends itself to compact construction.

The Pierce-type guns have found their widest applications in the European countries. The largest guns of this type normally used are capable of beam powers of up to 150 to 200 kw at 200 kv, though a single gun developed by Ardenne in East Germany is rated at 1700 to 2000 kw.

The second type of gun is the transverse-field linear gun[46]. These guns are self accelerating, are simple and rugged in design, and can be scaled up to virtually any power level desired. The entire unit, shown in figure 21 is immersed in a magnetic field in which the field lines are parallel with the filament. The linear beam of electrons which emerges between the accelerating anodes can be bent and focused by the field as appropriate to the process. Advances in the control and configuration of the beam-focusing and deflection fields have permitted much greater

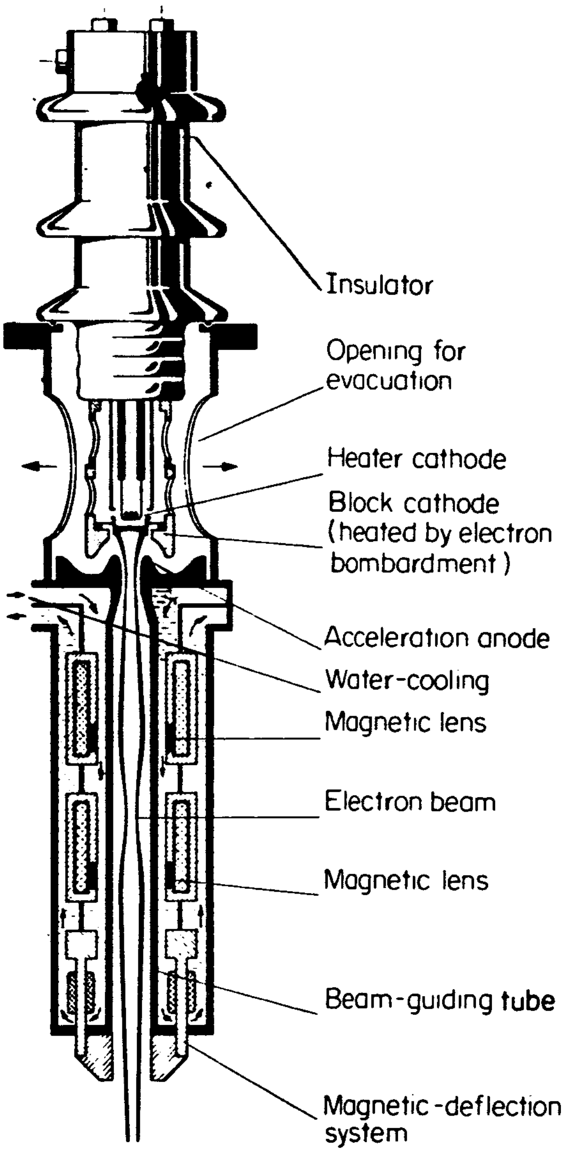


FIGURE 20. SCHEMATIC OF A PIERCE-TYPE ELECTRON-BEAM GUN[47]

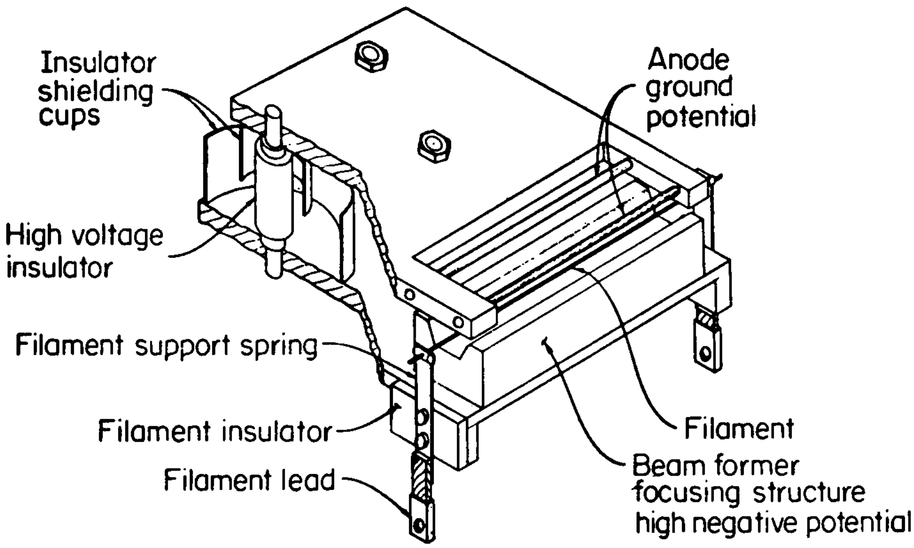


FIGURE 21. SCHEMATIC OF A TRANSVERSE-FIELD LINEAR ELECTRON GUN(46)

flexibility in gun location. Current practice is to locate the guns out of the line of sight of the molten pool so that emitted vapors, gases, and splatter cannot interfere with gun operation. Guns are usually located in a separately pumped chamber which has sufficient pumping capacity to minimize the effects of pressure excursions in the main chamber.

The largest transverse guns commonly used are rated at ≈300 kw; however, this type of gun has a greater scale-up potential than the Pierce-type gun because of inherent limitations(46, 47) for Pierce guns. These maximum powers have apparently not yet been reached.

Vacuum pumping systems: Electron beam processing in most instances requires high vacuums for two reasons. First, the purifying action observed for EB melting is a direct result of the exposure of large surface areas of the molten material to the high-vacuum atmosphere. Second, the EB guns discussed above require high vacuums for efficient operation, approximately 5×10^{-4} torr maximum. Because of the generation of gaseous materials during melting, high pumping capacities are also required in order to maintain the vacuum.

In both of the guns discussed above, electrons are released from the cathode by thermionic emission. If the pressure is allowed to rise in the furnace, a glow discharge will occur due to the ionization of the gas molecules in the furnace, and the current will rise markedly. Since a hot cathode is present, chances are good that an arc will develop(48). If this happens, either the power supply will be overloaded because of the low resistance of this form of discharge or the gun and fittings will be destroyed by the violent heat of the arc.

Power supplies: The basic power requirements of an electron beam melting system are a high-voltage dc source of relatively low current for the actual melting energy and a thermal emitter supply of much lower ac voltage and high current. Power requirements for a specific system depends upon the evaporation rates of the material as well as upon its melting point. The power supply must provide independent voltage and current control so that a required power input can be achieved by a range of voltage-current settings(49). Such flexibility provides high-voltage startup and the subsequent establishment of optimum operating power conditions commensurate with the characteristics of the melt stock. The power supply typically requires currents of 1 to 20 amps at voltages between 3 and 20 kw.

The only special feature of the filament power supply is that it must be insulated against high voltage(50). This unit is equipped with an emission current controller on the cathode which serves to stabilize the operation, particularly with regard to rapid recovery after a voltage breakdown.

Quality of electron-beam-melted materials: Electron beam melting purifies metals by the volatilization of impurities. The amount of volatilization depends on (1) the length of time the materials spend in the molten

state, (2) the pressure of the furnace atmosphere, (3) the temperature of the molten material, and (4) the composition of the material being melted (including impurity concentration). The first two conditions represent the primary reason for the improved purity of EB-melted material over vacuum-arc or induction-melted materials. EB melting typically is conducted in a much higher vacuum than is arc melting and the molten metal during EB melting is exposed to the high-vacuum environment for a longer period of time.

Only those impurities with vapor pressures higher than that of the base material will be preferentially removed during melting. In the section dealing with Physicochemical considerations, the feasibility of deoxidizing a given metal by vacuum melting was evaluated by examining the oxygen-to-metal ratio in the vapor relative to that in the metal at equilibrium: $[(O/M)_{vapor}/(O/M_{metal}]$. When this ratio is significantly greater than unity, e.g., 100, the metal is subject to efficient deoxidizing by vacuum melting. When the ratio is above but near unity, the concurrent loss of metal would be prohibitive. In table 10 the feasibility of purifying a number of metals by vacuum melting is predicted. The separation of elements into two groups is based on the data presented in table 4 and that published by Smith, Hunt, and Hanks[49]. It should be noted that the latter data must be used with discretion because in some instances the important oxygen-containing vapor species is not the monoxide phase assumed, but elemental oxygen or a higher oxide. The mechanism of metal oxide volatilization may be used to advantage in some metallic alloys[49]. For example, the deoxidation of molybdenum is possible by the loss of TiO from an alloy of molybdenum and titanium. For sufficiently small titanium additions, complete vaporization of the titanium can also be accomplished during the melting.

TABLE 10. - DEOXIDATION OF METALS BY VACUUM MELTING

Should Deoxidize	Deoxidation Impractical or Impossible
B	Be
Hf	Co
Mo	Cr
Nb	Fe
Si	Li
Sm	Mn
Ta	Ni
Th	Ti
W	V
Y	
Zr	

Thus, molybdenum may be more easily deoxidized by the addition of small amounts of titanium which forms TiO, a more volatile oxide. Both the titanium oxide and titanium are subsequently vaporized during the melting operation.

The electron beam melting of alloys is complicated by the possible preferential volatilization of alloying elements. Any alloying element having a higher vapor pressure than the base metal will be removed to some extent during electron beam melting. The degree of vaporization loss of alloying elements can, however, be calculated with sufficient accuracy for many materials and may be compensated for by overcharging these elements in the melting stock.

Aside from the higher purities typically observed in EB-melted materials, ingots of EB-melted materials are characterized by large grains and poor surface quality(51). Both of these features are a direct result of the low melting rates that are used to obtain maximum purification. In addition, electron-beam melted materials typically have lower strengths and higher ductilities than materials produced by other fabrication techniques. This is primarily due to the decreased interstitial impurity content in these alloys. This has been especially true for the refractory metals, and the increased ductility has resulted in increased fabricability of EB-melted refractory metals. A similar effect has been shown for EB-melted Type 304 stainless steel as demonstrated by the work-hardening curves shown in figure 22(52).

Furnace designs.

Drip or pool melting: Three melting methods that may be described as either drip or pool melting and that are currently used on an industrial scale are schematically illustrated in figure 23. A solid bar may be fed vertically or horizontally into the beam and drip-melted, or granules may be fed directly into the molten pool. An open bottom water-cooled copper mold is typically used and the ingot is withdrawn through the bottom so that the molten-metal pool is always on the upper rim of the mold. In figure 23 these melting methods are represented with Pierce-type electron beam guns; however, remote transverse guns may also be used. In this case magnetic fields are used to focus the electron beam onto the feed material and the molten bath. A variation of the bath-melting technique is the use of a solid-bottom water-cooled copper crucible. During melting a solid skull of the material melted forms on the surface of the crucible and prevents crucible reactions. Once a sufficient amount of molten material is produced, it can be tilt-poured into a mold of the desired configuration.

The largest existing electron beam furnace is of the drip-melting type(53). This furnace, located in East Germany, operates at a power rating of 1.7 megawatts, and is primarily used to drip-melt steel-alloy ingots about 30 inches in diameter and an estimated 10 feet long, weighing up to about 13 tons. On the basis of the performance of this unit, a 7 megawatt drip-melting unit is projected.

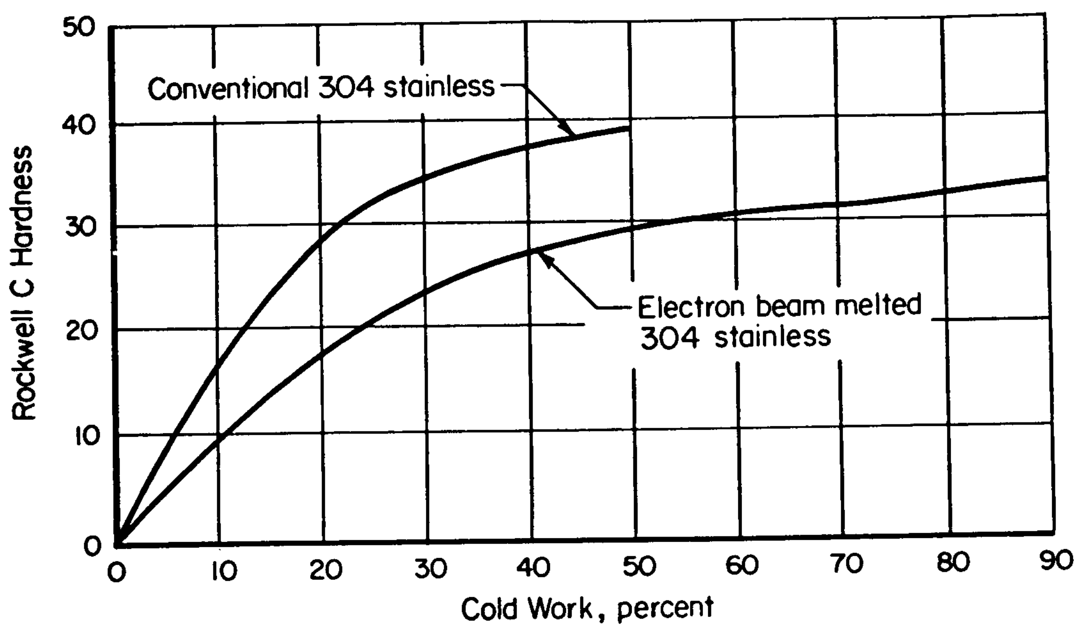
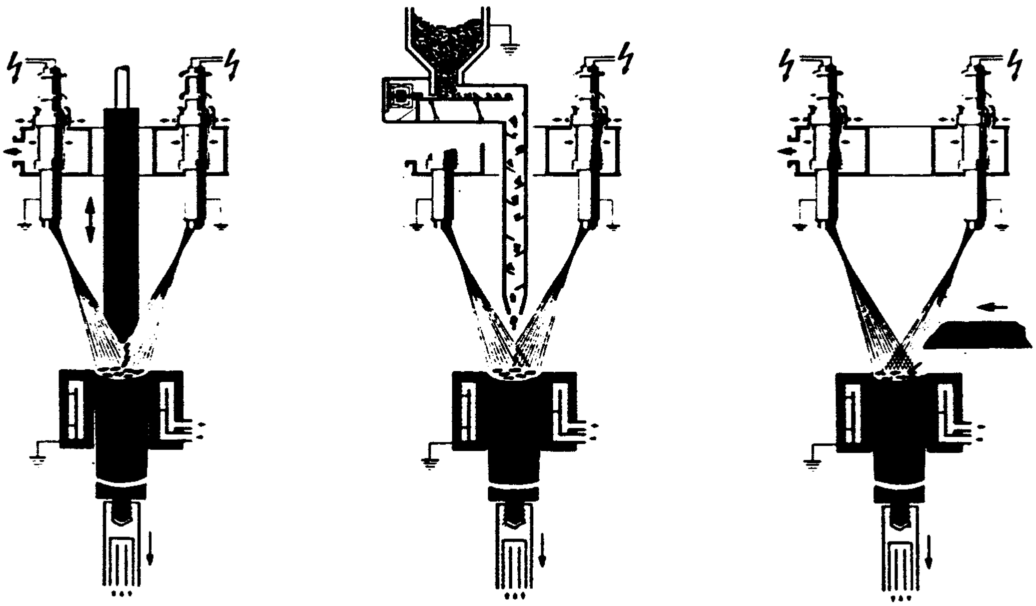


FIGURE 22. WORK-HARDENING CURVES FOR STAINLESS STEELS[52]



Drip Melting With Vertically Fed Consumable Electrode

Bath Melting of Granules

Drip Melting With Horizontally Fed Consumable Electrode

FIGURE 23. SOME TYPICAL FURNACE DESIGNS FOR DRIP AND POOL ELECTRON-BEAM MELTING(47)

Cold-hearth melting(46, 54, 55): A schematic of the hearth furnace developed at Airco-Temescal is shown in figure 24. Because of the hearth configuration it is possible to feed charge material into the furnace in almost any form including ingots, powders, chunks of scrap metal, or turnings. Initial melting is performed in the melting zone and the gross impurities including dissolved gases and volatile metallic contaminants are eliminated. This initial purification is carried out in a zone at a somewhat higher pressure than the rest of the furnace ($\approx 10^{-2}$ torr) so that gross-impurity removal can be accomplished more efficiently. The material then flows under a slag barrier which prevents solid contaminants on the surface from flowing into the next stage of purification. In this section, the material is subjected to a higher vacuum, and thermal stirring produces an homogenizing effect on the melt. The hearth, constructed of water-cooled copper, thus reduces the possibility of reactions between the molten metal and the hearth material. The high rate of heat extraction by the water-cooled copper hearth decreases the economy of the process slightly by requiring excess electron-beam powers to compensate for the cooling action of the hearth. According to experience to date in a large pilot-plant furnace, the resulting thermal inefficiency has not been found to be a serious economic problem. Insulating liners may be used in the hearth to provide higher thermal efficiency for the processing of relatively nonreactive materials.

The area of the hearth is large enough to allow exposure of molten metal to the vacuum environment at a rate of about 300-500 $lb/hr/ft^2$ of hearth. The electron-beam heating requirement is in the range of 20 to 50 kw/ft^2 of hearth depending upon the scale of the operation. For the largest projected scale of operation (1 million tons of steel per year) the EB power requirements would be on the order of 80 kwh per ton of steel. The controlled flow of molten material through the hearth permits continuous casting of slabs or ingots.

A recent improvement in this process has been the addition of an induction-heated crucible and ladle transfer system to the input stage of the cold hearth furnace(55). This system provides a means for preliminary degassing of the molten-feed stock and performing some of the refining operations that would otherwise not take place on the hearth. It also provides a molten feed to the hearth which results in economy in capital and operating expense and also improves the stability of the hearth itself. A pilot-plant furnace of this type is now in operation at Airco-Temescal, and the design of a full-scale furnace rated at 20,000 to 30,000 tons per year capacity has been proposed.

Plasma electron beam melting: Plasma electron beam melting is discussed here as a subject separate from high-vacuum EB melting because of the fundamental differences between these techniques. The main distinguishing feature of plasma EB melting is that the process is conducted in a relatively high-pressure (10^{-1} to 10^{-4} torr) inert-gas

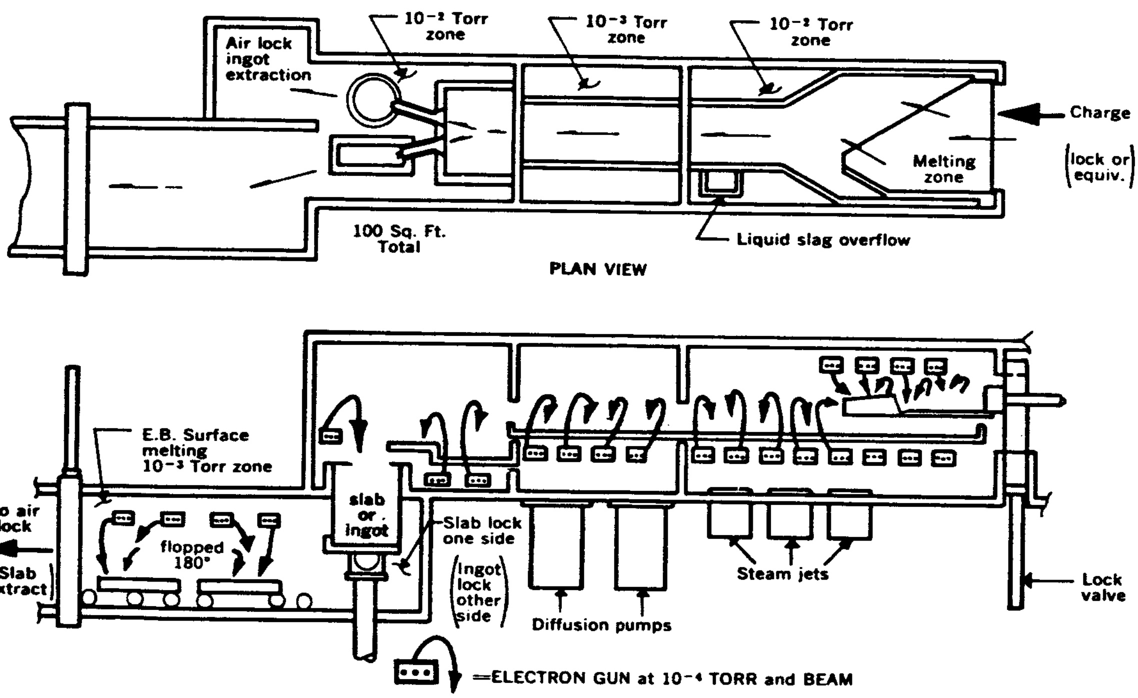


FIGURE 24. SCHEMATIC OF PROPOSED ELECTRON-BEAM-HEATED COLD-HEARTH FURNACE USING SOLID CHARGE MATERIAL(54)

atmosphere in contrast to the high vacuum (10^{-4}-10^{-6} torr) required for conventional EB-melting techniques.

Two distinct types of plasma electron-beam (also referred to as hollow cathode) units are discussed in the literature. One reported by van Paassen, Muly, and Allen[56] and later by Cocca and Stauffer[57] operates at 10-to 20-kv potential and 10 ma to 2 amps of electron-beam current in an inert-gas atmosphere at pressures between 1 and 100 microns (10^{-1} to 10^{-3} torr). The cathode in this unit is a cylindrical or spherical hollow wire-mesh container. The cathode for this process remains cold, and the electron beam is extracted primarily by secondary emission from the ion-bombarded cathode. The second type of hollow-cathode gun was first reported upon by Lindsky, et al.[58], and later by Morley[59]. During operation a hot, solid-wall, tubular cathode contains a low-pressure gas plasma from which an electron beam from 100 to 1,000 amps can be extracted at a potential of from 30 to 50 volts. For best efficiency of operation, this unit operates from 10^{-4} to 10^{-2} torr, but excursions in the 10-torr range may be tolerated with some loss of overall beam efficiency. In this process the electron beam primarily consists of thermionically emitted electrons from the cathode (heated by ion bombardment) together with excess electrons contained in the plasma. These two types of hollow-cathode electron guns are distinguished by referring to them as cold and hot hollow-cathode guns, respectively.

The hot and cold hollow-cathode melting schemes are similar in two respects. In both processes electron beams are generated by the bombardment of a cathode with high-energy, positive ions from a plasma. Also, in both schemes pressures greater than those necessary for efficient vacuum electron-beam melting are possible. This represents both an advantage and a disadvantage for plasma electron beam melting. The higher pressure conditions restrict the amount of purification by vaporization of volatile species to some extent; however, the purification by vaporization afforded by this technique is greater than that present in either vacuum arc or induction melting. The advantage of working in higher pressures than with standard vacuum EB melting is that the ease of melting alloys is increased because of the decreased tendency for vaporization loss of alloying elements. Thus with plasma EB melting it may be possible to strike a favorable compromise between the purifying action provided by EB melting and the control of composition provided by arc melting.

The primary differences in the two plasma electron-beam melting techniques discussed is in the nature of the electron beam produced. The hot hollow cathode produces a substantial fraction of the electron beam by thermionic emission from the hot cathode. The remainder of the electron beam consists of electrons from the ionized gas. The cold hollow-cathode process, on the other hand, relies primarily on secondary emission of electrons from the ion-bombarded cathode. Under certain power requirements, however, the cold hollow-cathode process may also produce a substantial fraction of thermionically emitted electrons. Power requirements

for the two processes represent decreased voltages from those typically required for vacuum electron-beam melting, but the power source for each unit is considerably different. The hot hollow cathode requires a low-voltage, high-current supply.

Hollow-cathode electron-beam melting has not yet become a commercial process, and the majority of work conducted has been on a small laboratory scale basis. However, the ability of this process to provide a purifying action in a relatively high-pressure-atmosphere furnace would appear to make it a candidate for the electron beam melting of alloys and in particular superalloy materials.

Application of electron beam melting to superalloys. - Little if any published information is to be found on electron beam melting of superalloy materials. The primary reasons for this apparent lack of attention are the difficulty of melting alloys in a high-vacuum environment because of differential vaporization problems and the high cost of small-scale electron beam melting.

In recent studies at Airco-Temescal a number of tons of superalloys such as Inco 718 and René 41 have been prepared in a 1200-kw cold-hearth electron-beam furnace. Preliminary results appear favorable according to Dr. H. R. Smith, Jr. The materials melted have held composition much better than previously expected, presumably because the molten alloys are not ideal solutions and vaporization rates are significantly less than the calculated values. Property evaluation of these electron beam melted superalloys are not complete at present; however, preliminary results suggest that the properties of these materials compare favorably with those of conventionally melted materials.

CHAPTER 6. VACUUM CASTING OF SUPERALLOY SHAPES

The Process

Vacuum casting of superalloy shapes is a development of the centuries-old lost-wax process. In recent times, pattern materials and mold materials have been improved to the point that the technology permits intricate parts to be made with high dimensional accuracy. The methods of making the mold have been exclusively the investing (i. e., coating) of a wax (or plastic) pattern with a refractory to obtain a strong mold[60]. Currently, some research work is being done using conventional 2-piece molds for large superalloy castings[61], but except for this, both large and small superalloy parts have been made by investment casting. The basic steps in the process are as follows:

(1) Make a wax or plastic pattern of the piece and add to it the gates, runners, and other parts of the molten-metal distribution system.

(2) Dip in a thin slurry of mold refractory, cover with "stucco" grain, dry. This is the shell mold.

(3) Heat the mold/pattern assembly to melt out the pattern, fire the refractory, and preheat the mold.

(4) Prepare the vacuum furnace and start the melt if the furnace has a separate vacuum chamber for the mold. This is done while the mold is being heated.

(5) Place the preheated mold in the vacuum furnace and transfer the molten metal to it.

(6) Remove the mold material, cut off the gates, runners, risers, etc., clean, and inspect the casting. This is done after the casting has cooled.

Advantages of investment casting, as applied to superalloys, in comparison with forged or welded assemblies, are[62]:

(1) Dimensional tolerances can be controlled relatively closely.

(2) Intricate designs can be made; in particular, internal passages in which air-cooled turbine blades can be cast.

(3) The stronger high-temperature alloys are not amenable to hot forging, and casting is now the only practical way to achieve the required shapes in these alloys.

(4) Fine surface finishes can be obtained, sometimes eliminating the need for polishing.

(5) Special microstructures such as unidirectional grains or single crystals can be obtained.[63]

In addition to these advantages, the use of vacuum in investment casting aids in filling the mold quickly and completely. Quickly transferred to the vacuum chamber, the preheated mold remains free of reactions with the atmosphere, while awaiting the molten charge. Details of various aspects of vacuum-investment casting are discussed in the sections that follow. Examples of cast turbine-engine components are shown in figures 25 and 26.

Making the Disposable Pattern

The disposable pattern in a high-production item is made by injecting wax or plastic into a steel or aluminum splite die machined to conform to the part shape, with allowances for wax shrinkage, metal shrinkage, and mold expansion. An overall figure of 0.5-percent wax shrinkage is accepted for most waxes. However, nonuniform shrinkage can cause dishing of flat surfaces where movement is restricted.[64] Most dies are machined from steel or aluminum to tolerances of 0.001 inch, and it is advised that a great deal of care be taken in preparing the die; nothing is saved if the die quality is sacrificed for economy.[65]

The lower half of the split die may contain a core if a hollow casting is to be made. Dies that incorporate ceramic cores must provide means of properly locating the cores so that they will not break as a result of stresses imposed on them. Provisions are made in the die for leaving the core ends exposed so that the core can be held in the investment mold. The part of the core protruding from the wax pattern is called the "core print".[66, 67]

The patterns for practically all turbine-balde shapes, even with intricate air passages can be made in a two-piece die. Other shapes require a more involved process. For example, patterns for turbine nozzles for small gas-turbine engines (figure 27) cannot be made in a single die from a one-piece wax injection. Similarly, the pattern for integrally bladed cast turbine wheels with twisted blading might not be removable as a one-piece injection. Two approaches to this problem are (1) to use soluble wax patterns as preplaced inserts between the blades or between the vanes, and later dissolving out the inserts, and (2) to make a compound built-up pattern of wax and plastic.

In the first approach, the preplaced inserts become part of the die, but after the wax injection they become part of the pattern.[68] They can be dissolved out by a weak hydrochloric or acetic acid solution.[64] Soluble wax is not always the best method if high dimensional accuracy is needed. It is especially hard to hold tolerances on massive parts when soluble-wax inserts are used[68], although they usually contain an inert filler.[64] A thin coating of wax over a plastic base would be an alternative way of obtaining a structurally stable, but easily removable, pattern for large castings.[69] Moreever, the wax/plastic assembly-casting method is said to be less costly and to offer greater design latitude than the soluble-wax technique.[70]

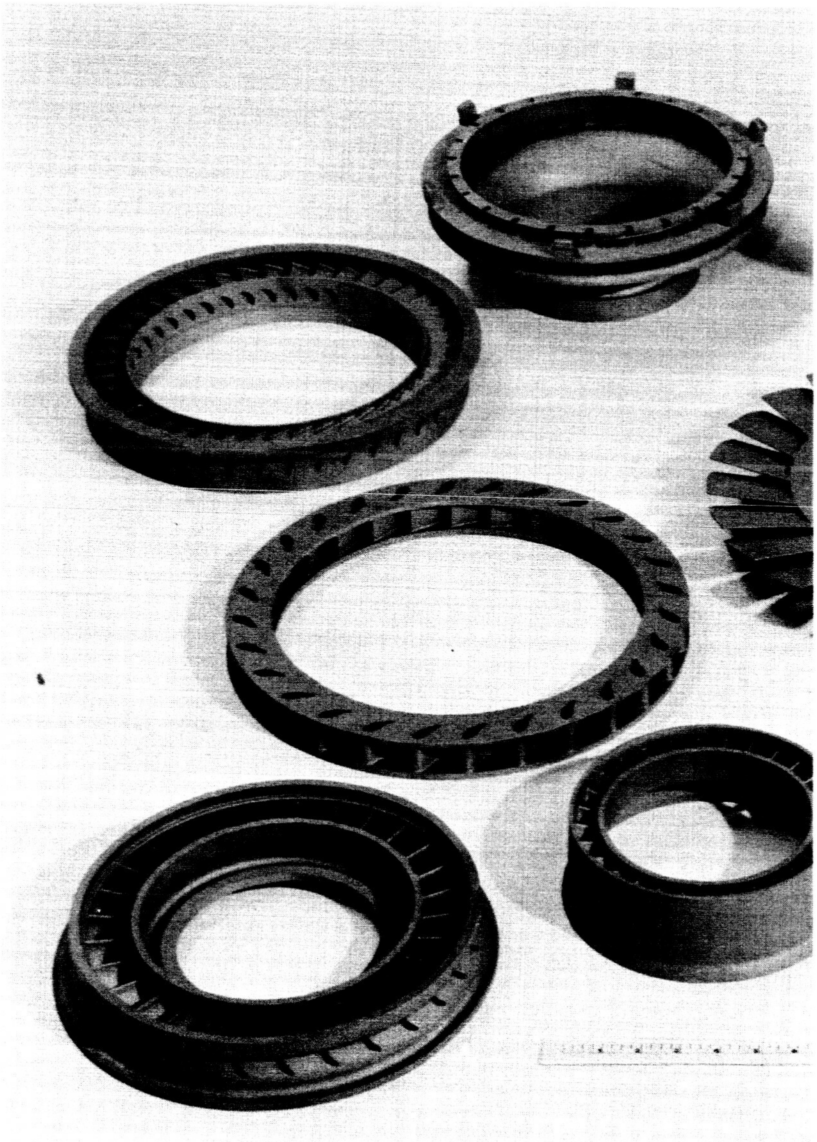


FIGURE 25. EXAMPLES OF PRECISION CAST NONROTATING COMPONENTS IN GAS-TURBINE ENGINES

(Courtesy Austenal Microcast Division, Howmet Corporation)

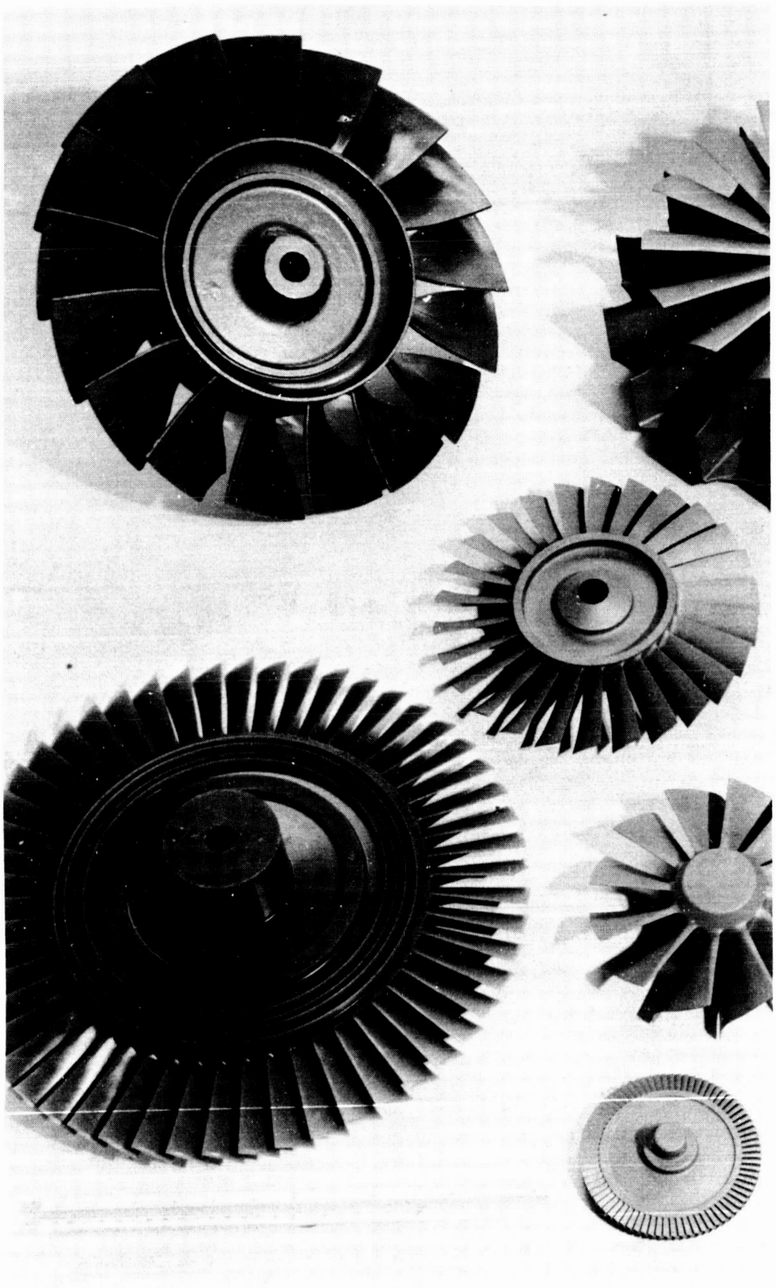


FIGURE 26. EXAMPLE OF PRECISION CAST ROTATING COMPONENTS FOR GAS-TURBINE ENGINES

(Courtesy Austenal Microcast Division, Howmet Corporation)

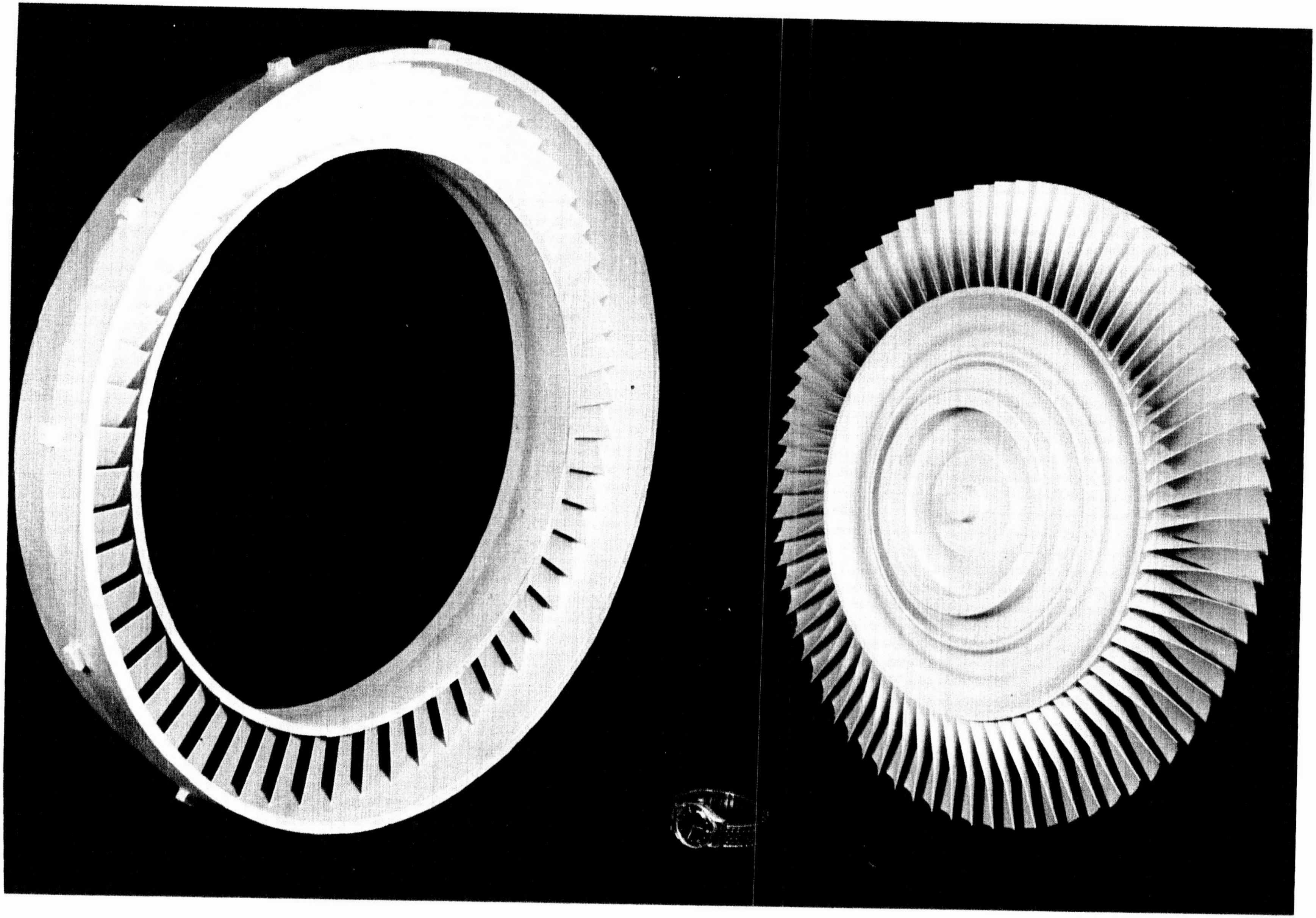


FIGURE 27. INVESTMENT-CAST NOZZLE (LEFT) AND AN INTEGRALLY BLADED TURBINE WHEEL FOR A SMALL GAS-TURBINE ENGINE

(Courtesy Misco Division, Howmet Corporation)

In the plastic/wax pattern method of forming such shapes as turbine nozzles, the individual plastic blades or vanes are cemented together in a fixture to form a ring. Previously cast wax patterns for the shrouds (on a nozzle) or the disk (on a turbine wheel) are joined to the plastic ring to form the final pattern. Figure 28 shows a plastic/wax pattern for a turbine wheel with integral blades. After inspection of this assembly, the wax gating system and pouring crucible are attached.(68)

In integral turbine wheel blades the choice of a one-piece, soluble-wax, or plastic/wax pattern depends on the size and shape of the airfoils, the accuracy required, and the total production expected (which influence the amount of money that can be spent on die construction). A high-quality one-piece wax-injection die costs about three times as much as the plastic/wax tooling, so that the latter is preferred during the development work where tooling cost, lead time, and tooling flexibility are important factors. In volume production, a one-piece wax die should be used if the design permits.(68)

Sometimes the designer can work with the foundry to change the design slightly in order to simplify the pattern-making process. For example, if the curvatures of the blade do not permit retraction of the plastic inserts, then soluble-wax cores or collapsible inserts are required.(68)

When the die is clamped and the cores and inserts are in place, hot wax is injected into the die to produce the patterns. Various presses are available commercially for accomplishing this operation. Typically, the molten wax is at 135 to 160 F and the injection pressures may be from 200 to 400 psi for turbine-blade patterns. The wax compositions are considered proprietary; one formulation used in early 1960's was 60-percent paraffin, 25-percent flexoresin, and 15-percent carnuba wax.(71) Present technology is based on synthetic waxes that have wider possibilities for adjusting the flow and solidification, the wax may contain 25-to 40-percent fillers consisting of such materials as polystyrene, or wood flour.

In making the wax pattern, several variables must be controlled. These include mold temperature, wax-injection temperature, dwell time, clamping pressure, injection pressure, and sometimes room temperature. These variables are all important in minimizing pattern shrinkage and obtaining complete filling of the die.

Specific values of each of the variables are fixed for each pattern, but the value depends on the size and complexity of the part and on the wax being used. The mold temperature, which is usually about 100 F, may affect the filling and can be increased if good detail is not obtained. It must be kept constant if the defect known as "flow lines" is to be prevented.(62) Generally, it is desirable to minimize the wax-injection temperature in order to reduce the amount of shrinkage after the pattern is removed from the die. Room temperature, especially in the summertime or in warm climates, should be controlled for maximum dimensional stability of the wax pattern.

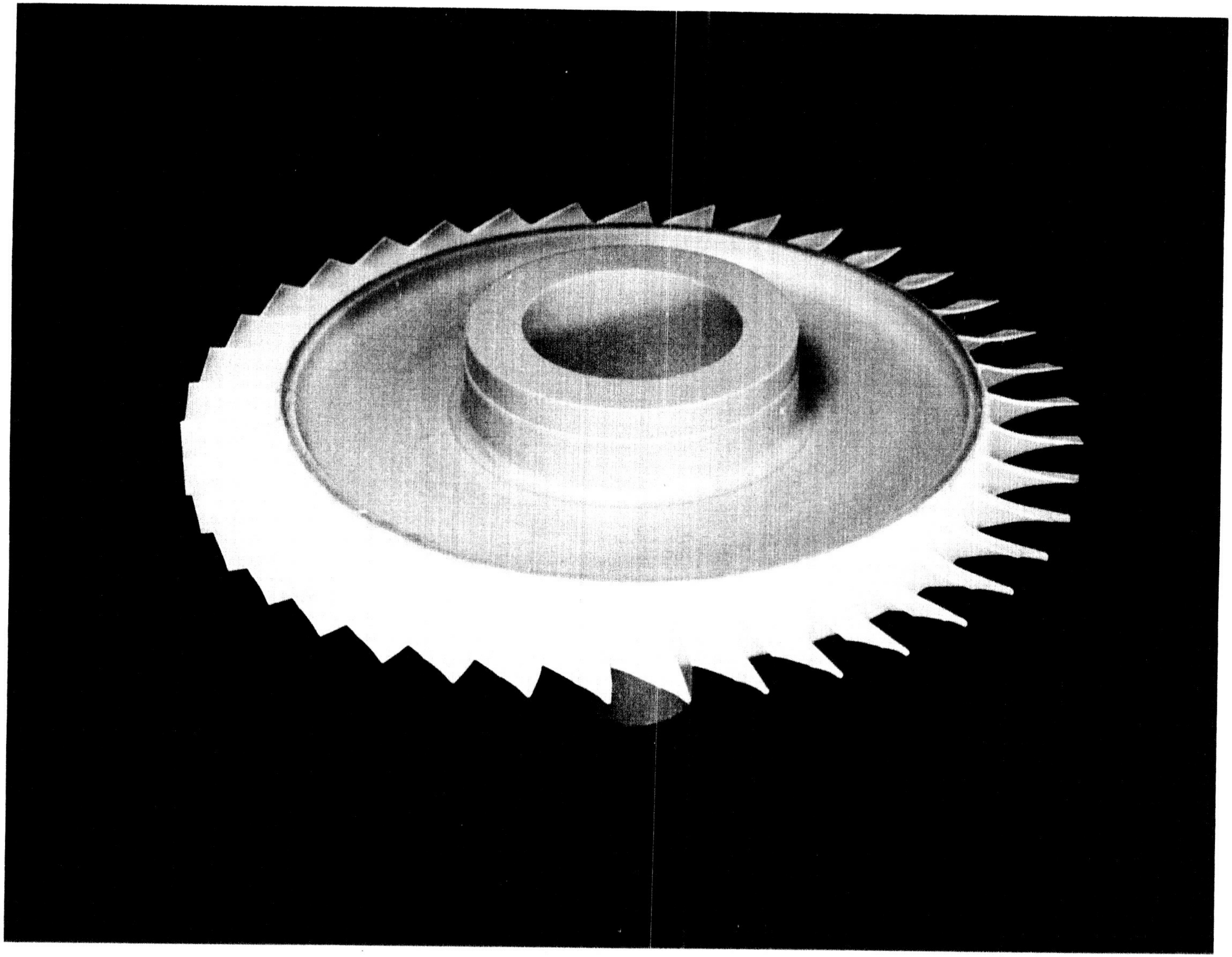


FIGURE 28. PLASTIC BLADE PATTERN ATTACHED TO WAX DISK PATTERN READY FOR ATTACHING THE PERFORMED PATTERN FOR THE POURING CRUCIBLE

(Courtesy MISCO Division, Howmet Corporation)

Clamping pressure and injection pressure are related. High injection pressure is, as a rule, desirable, but if excessive flash occurs at the die-parting line, it may be necessary to increase the clamping pressure. (Good die fit-up is, of course, a first requirement for minimizing flash.)

Slow setting, fluid waxes require colder molds than fast setting waxes. With fast setting waxes it is preferable to heat the mold rather than overheat the wax, for even a 5-degree overheating from predetermined limits can cause excessive shrinkage and "dishing" of flat surfaces. Because hot wax gives a better surface, there is a tendency in the direction of overheating. A better method is to use cooler wax with higher pressure.[64]

Plastics are sometimes used as patterns for long-run small parts of simple geometry because they are less costly than wax and can withstand more abuse during handling. For cored parts, however, only waxes are used because the plastics, being highly viscous, require higher injection pressures and are difficult to remove.[67] Plastic materials require molding pressures of 10,000 to 30,000 psi, temperatures of 325 to 600 F, and clamping pressures up to 500 tons.[72]

Dimensional accuracy of the casting is very dependent on the accuracy of producing and assembling the patterns. Contraction and distortion of the wax pattern, when it has been removed from the die, may continue for 28 to 48 hours because of stress in the material and varying cross sections. This can be combated by coring out or inserting a chill in heavy sections; minimizing the temperature of the wax, perhaps injecting it as a semisolid instead of a liquid; and placing the hot pattern in a plastic receiving fixture (facsimile) when it is taken from the die.[73] Some data on the benefits derived from this practice are shown in table 11.

The finished separate patterns are assembled in a cluster and fused to the gates, runners, etc., with a hot knife or similar tool as illustrated in figure 29. Cement and solvents are used for joining plastic patterns to the gates and runners.[67] It is sometimes recommended that the sprue wax have a melting temperature below that of the pattern wax[64], so that the wax can be melted out without stressing the mold, but this is not always done. Usually, however, little or no filler is used in the wax for the gates, runners, and sprues. Stress due to expansion during wax removal can be avoided by using a thin wax shell for the pouring basis with an aluminum plug to fill the large volume. Threads in the plug are a convenient way of attaching a handle for dipping and drying. Figure 30 illustrates the way a plug might be used. The finished pattern may be cleaned in alcohol, but the pattern must be thoroughly dried afterwards.



FIGURE 29. ATTACHING THE WAX PATTERNS FOR THE POURING BASIN AND SPRUES TO THE CASTING PATTERN BY MEANS OF AN ELECTRICALLY HEATED TOOL

(Courtesy TRW Metals Division)

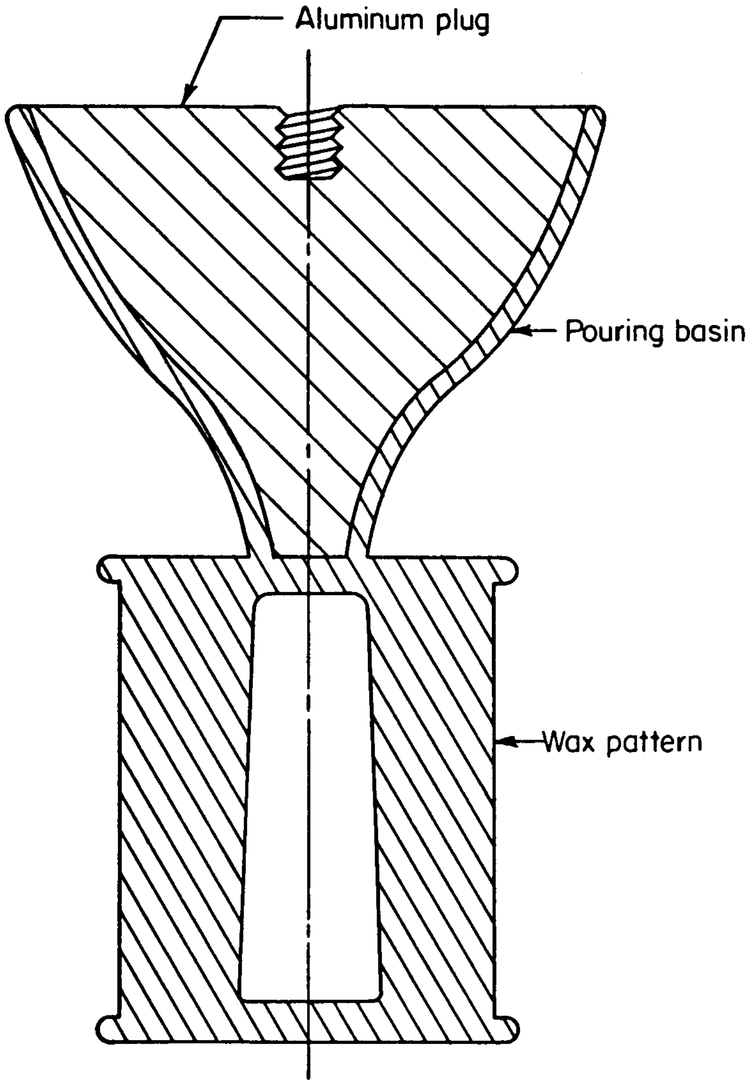


FIGURE 30. WAX PATTERN WITH ALUMINUM PLUG IN POURING BASIN

TABLE 11. DISTORTION OF WAX PATTERNS COOLED FREELY AND COOLED IN A PLASTIC FACSIMILE[73]

Part	Kind of Distortion	Amount of Distortion	
		Cooled Freely	Cooled in Plaster
Stator segment	Axial, on a 5-in. length, in.	0.020-0.030	0.005-0.010
	Blade bowing on a 5-in. length, in.	0.010-0.020	Nil to 0.005
Turbine blade	Twist on a 5-in. length, degrees	3-4	Nil to 1

Molds and Cores

The next step in the process is to invest the wax pattern with the molding material by successive dips in ceramic slurries to make a one-piece shell mold. For hollow parts, a hollow-core wax pattern is dipped, the same as for a solid pattern. However, if the core of a hollow airfoil section is too small for the investment to fill successfully, it is necessary to use a preformed removable core as part of the pattern around which the rest of the mold is formed.[65] This is illustrated in figure 31.[74] Today, all air-cooled turbine blades (such as illustrated in figure 32) are made with preformed cores, examples of which are shown in figures 33 through 35. Figure 36 shows the assembly of a wax pattern containing a preplaced core.[67] Structural hollow parts – struts, for example – might be made by dipping the pattern.

Core materials and techniques. – Silica cores are used for many complex configurations, the most prevalent today being for air-cooled turbine blades. For holes 0.020 to 0.120 inch in diameter, which are used for straight-through cooling of turbine rotor blades, stabilized quartz tubing as well as ceramic tubes have been used as the core material.[65,75] Figure 37 shows quartz tubes protruding from the wax pattern of an air-cooled turbine airfoil. Figure 38 is the mold (made from this pattern) cut apart to show the core placement.[67] Today, silica (or enough silica to make the core leachable in caustic) seems to be used exclusively, because of the ability to remove it without affecting the casting's properties. For massive and complicated cores, complex silicate compositions[62,65] and other proprietary ceramic compositions have been used successfully.[66] In general, the latter are magnesium-aluminum silicates, called cordierites.

Cores are usually made to tolerances of +0.005 inch, although closer tolerances are possible in some instances.[74] Ceramic tubes have been ground with a very high level of dimensional accuracy. The designer should

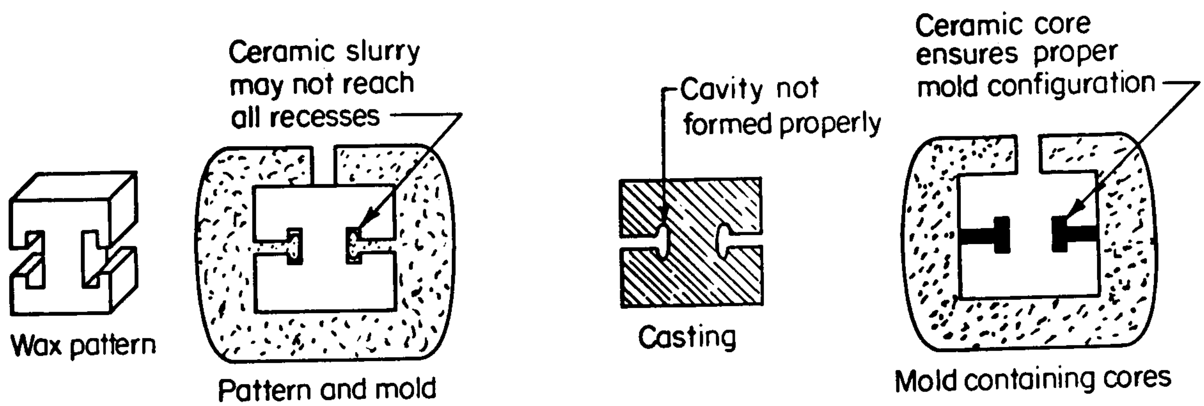


FIGURE 31. EXAMPLE OF THE USE OF A PREFORMED CORE TO PRODUCE ACCURATE HOLLOW OR SEMIHOLLOW CASTINGS[74]

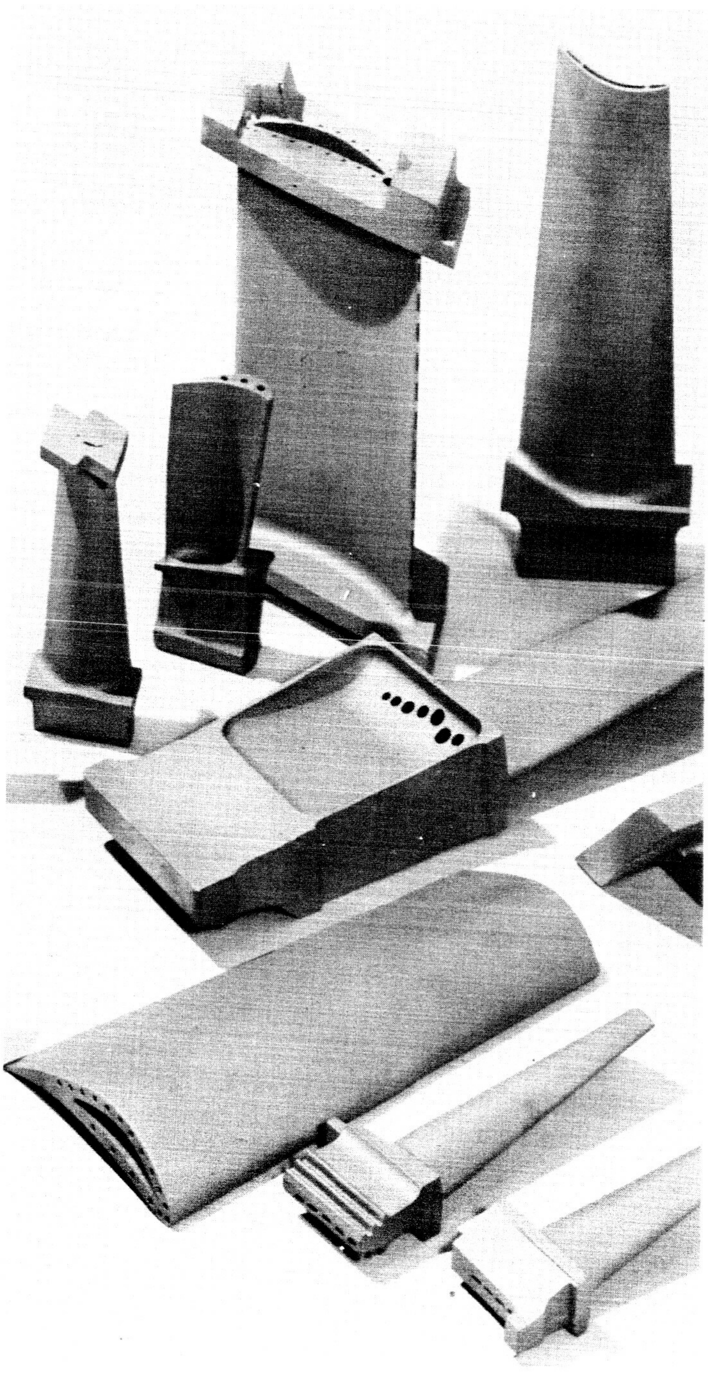


FIGURE 32. EXAMPLES OF AIR-COOLED TURBINE BLADES

(Courtesy Austenal Microcast Division, Howmet Corporation)

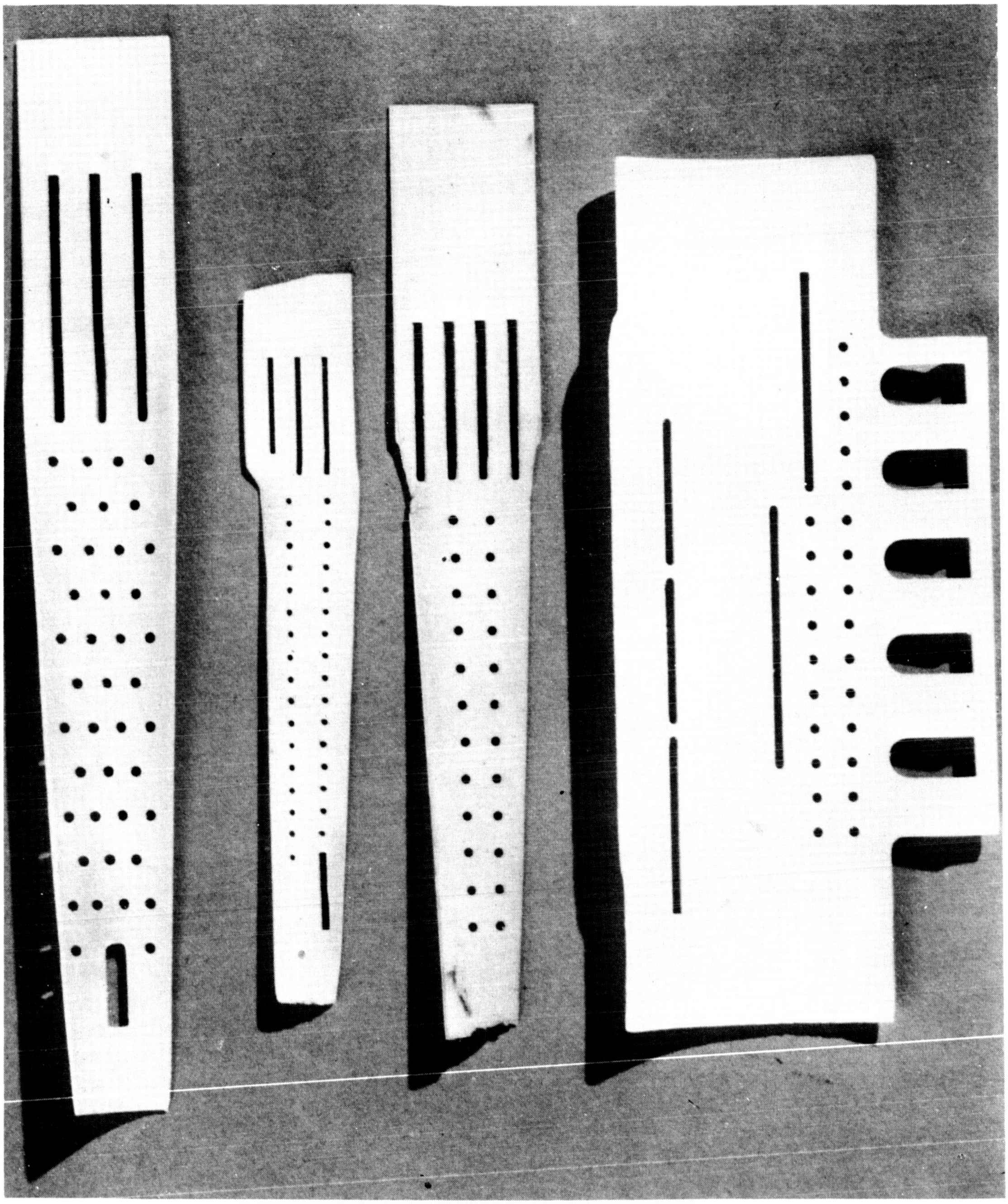


FIGURE 33. EXAMPLES OF PREFORMED CERAMIC CORES FOR AIR-COOLED TURBINE BLADES

(Courtesy Superalloy Group, Howmet Corporation)

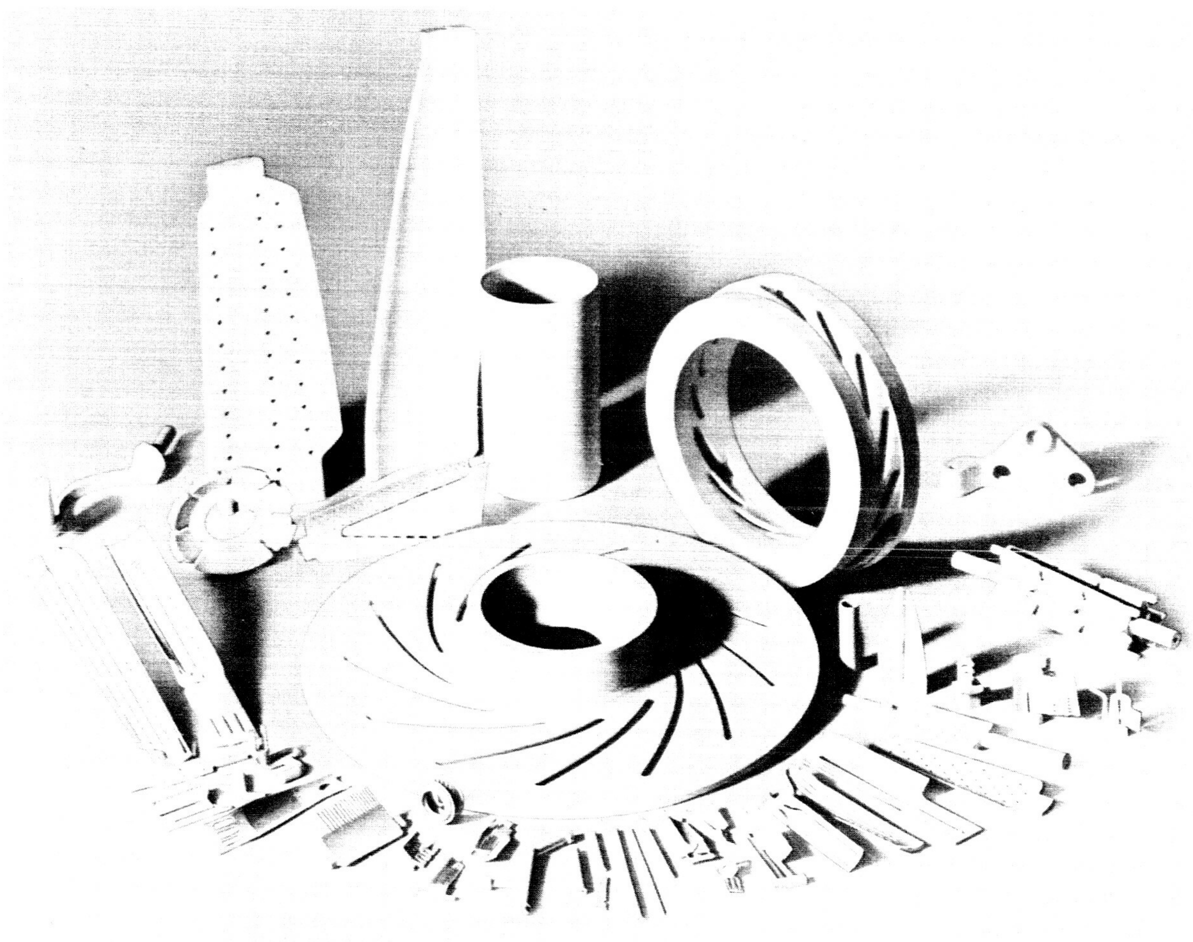


FIGURE 34. PREFORMED CERAMIC CORES FOR VARIOUS APPLICATIONS

(Courtesy Sherwood Refractories, Inc.)

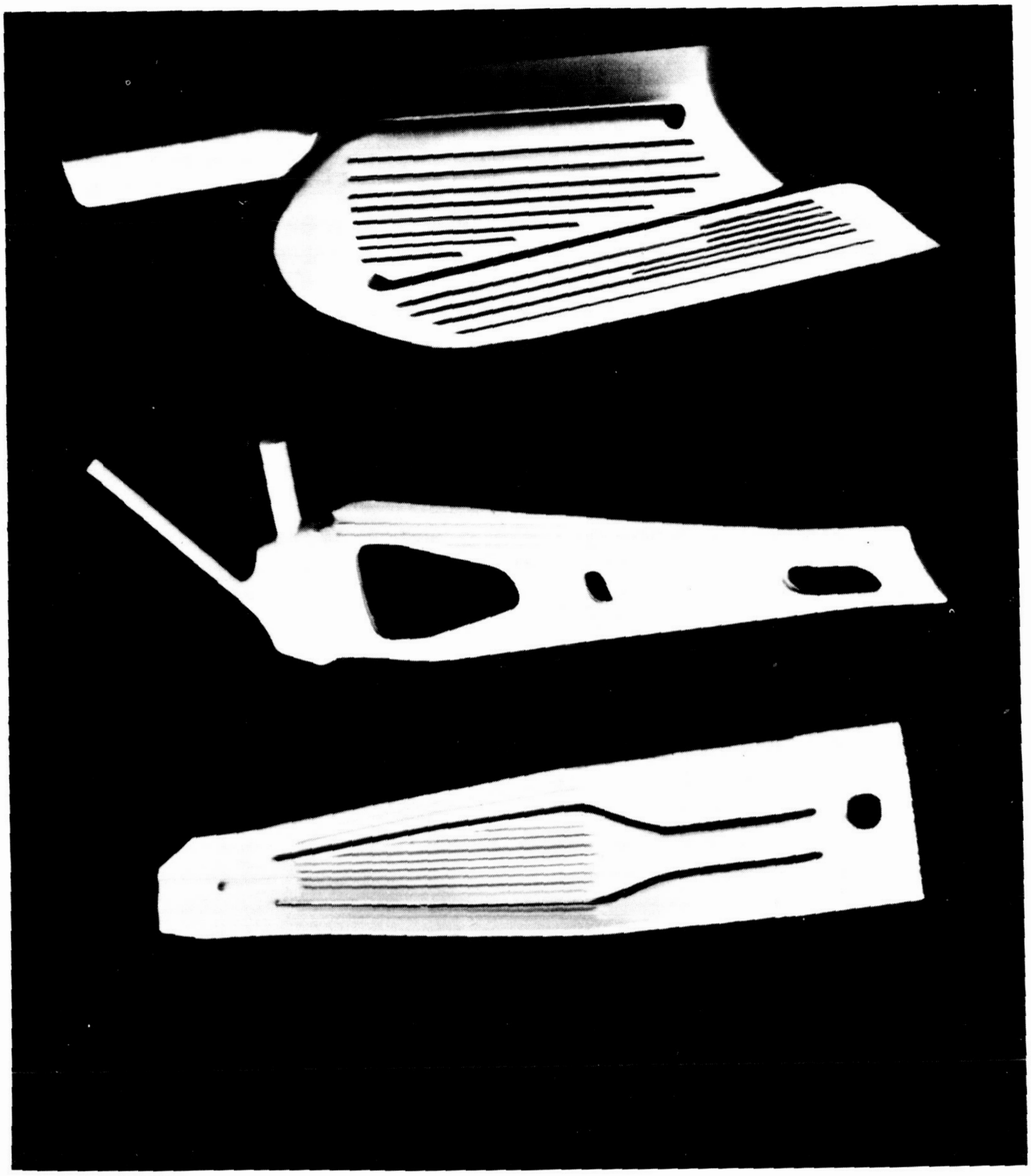


FIGURE 35. PREFORMED CERAMIC CORES FOR AIR-COOLED TURBINE BLADES

(Courtesy Sherwood Refractories, Inc.)



FIGURE 36. ASSEMBLY OF WAX PATTERNS CONTAINING A PREPLACED CORE

(Courtesy Martin Metals, Division of Martin-Marietta)

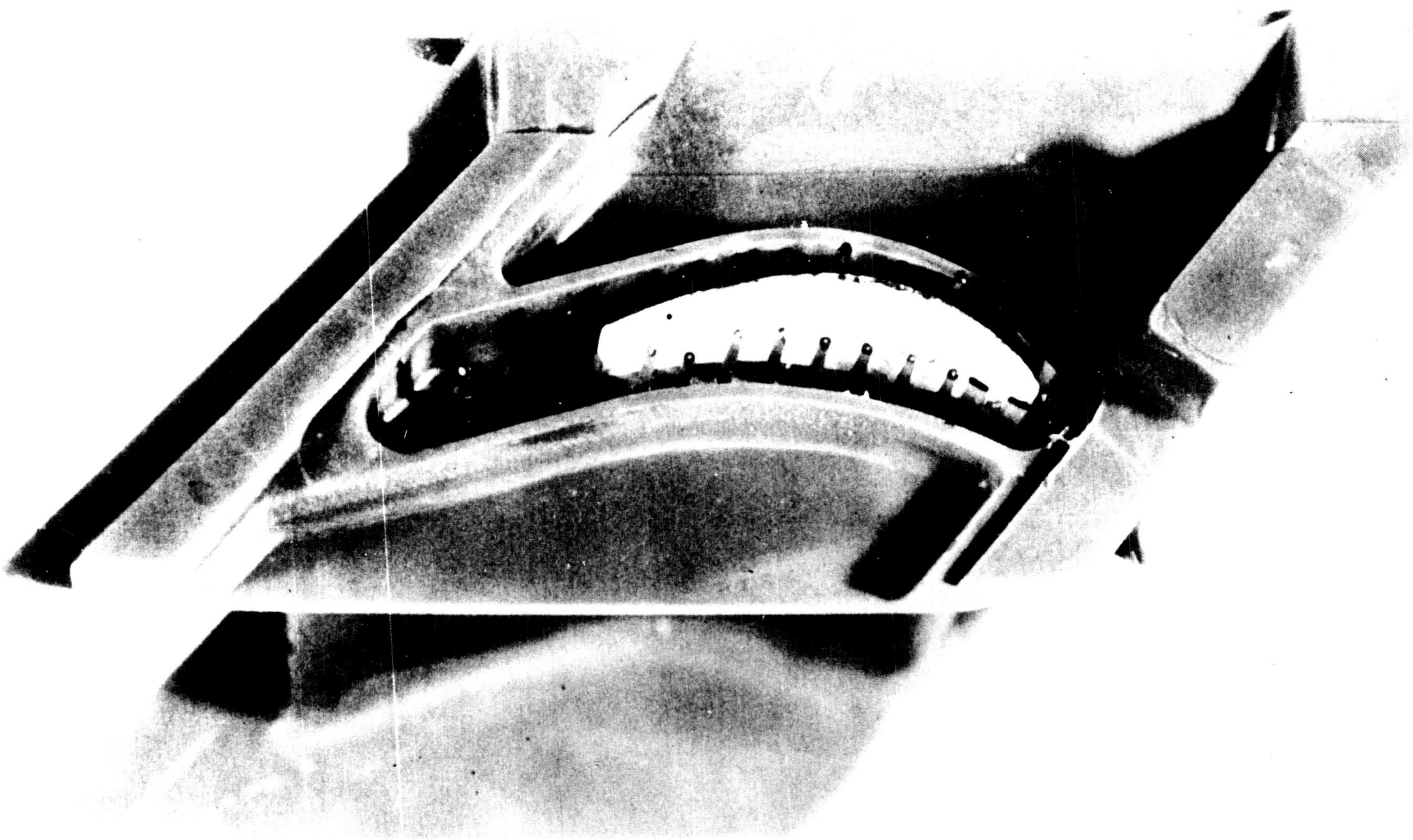


FIGURE 37. QUARTZ TUBING CORES PROTRUDING FROM WAX PATTERN FOR AN AIR-COOLED TURBINE AIRFOIL

(Courtesy Martin Metals Company)

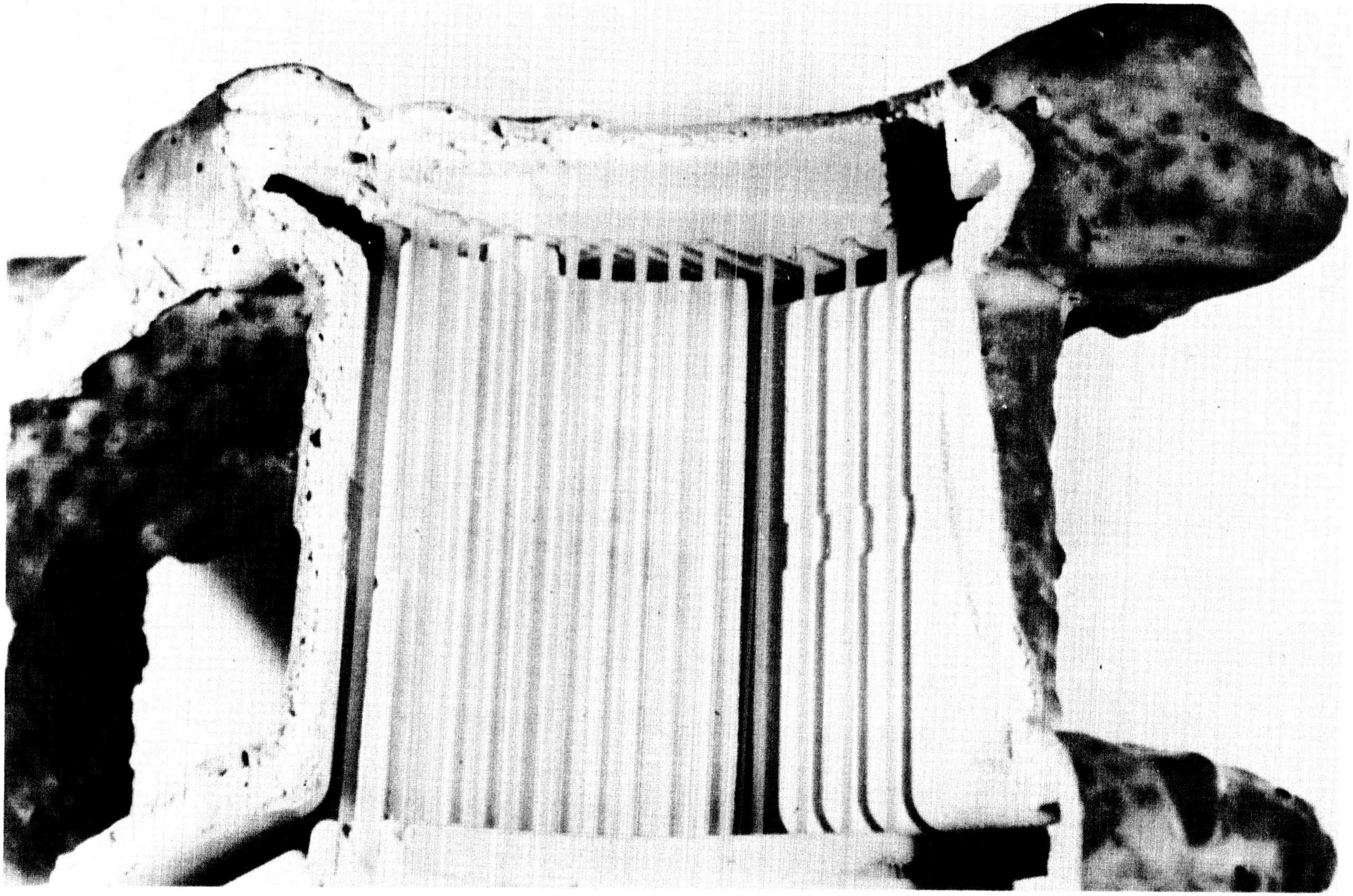


FIGURE 38. MOLD MADE FROM PATTERN SHOWN IN PREVIOUS FIGURE
(Cut apart to show core placement)

(Courtesy Martin Metals Company)

keep in mind that high core precision is costly and should not be "over specified". The silica compositions used today seem to have adequate mechanical strength, crushability, resistance to thermal shock, dimensional stability, inertness to molten alloys, and refractoriness (ability to retain their shape at high temperatures) and are relatively easy to remove from the casting. To help maintain dimensional stability during firing, the cores might be fired in ceramic setter blocks which conform to the core shape. Also, they may be simply backed by loose grog during the firing.

Preformed cores must be rugged enough to withstand handling in foundry operations, but their strength must also be maintained through the preheating range. Distortion during this period cannot be tolerated. Because of the necessity of maintaining dimensional tolerances on thin sections, the shrinkage of the core must be compatible with mold shrinkage during all the mold-preparation steps; otherwise, distortion or breakage of the core will result. Removal of the cores, by whatever method, must be accomplished without damaging the casting.

Preformed ceramic cores have been made by all the usual ceramic forming methods. These include extrusion, dry and wet pressing, casting, isostatic pressing, injection molding, and various combinations of these processes. Extrusion is used for round, or other regular cross sections, usually as cores for straight-through passages in turbine airfoils. However, the extrusions can be bent or formed if necessary.

Ceramic casting processes are also used when a few castings are to be produced for prototype work as well as for certain production items. The ceramics are bonded by air-setting, thermal-setting, chemical, or hydraulic reactions. Molds for casting the ceramics include plaster, metal, wax, and plastic; filling of the mold is aided by air pressure and vibration. For high-volume production, ceramic injection molding or transfer molding is more economical, even though the first cost of tooling is higher. Complex labryinth cores for hollow blades can be made in standard plastic-injecting molding equipment or by transfer molding; in these cases the ceramic material is mixed with a thermosetting resin binder. Transfer molding is preferred over injection molding because, in the former, a stronger core is obtained in both the green state as well as in the finished core. Preweighed pellets are placed in the die and molded as shown in figure 39.

Proprietary core materials may contain alumina, magnesia, zirconia, and silica, alone or in combination.(75) It has been reported that alumina-base cores for a hollow turbine blade are not satisfactory.(66) Alumina combinations formed by casting, compression, or injection molding were too weak during the sintering stage, and the manufacture of thin cores, or airfoil cores with thin leading or trailing edges was not considered to be practical. Moreover, removal of these cores (even by sandblasting) was difficult and uneconomical.

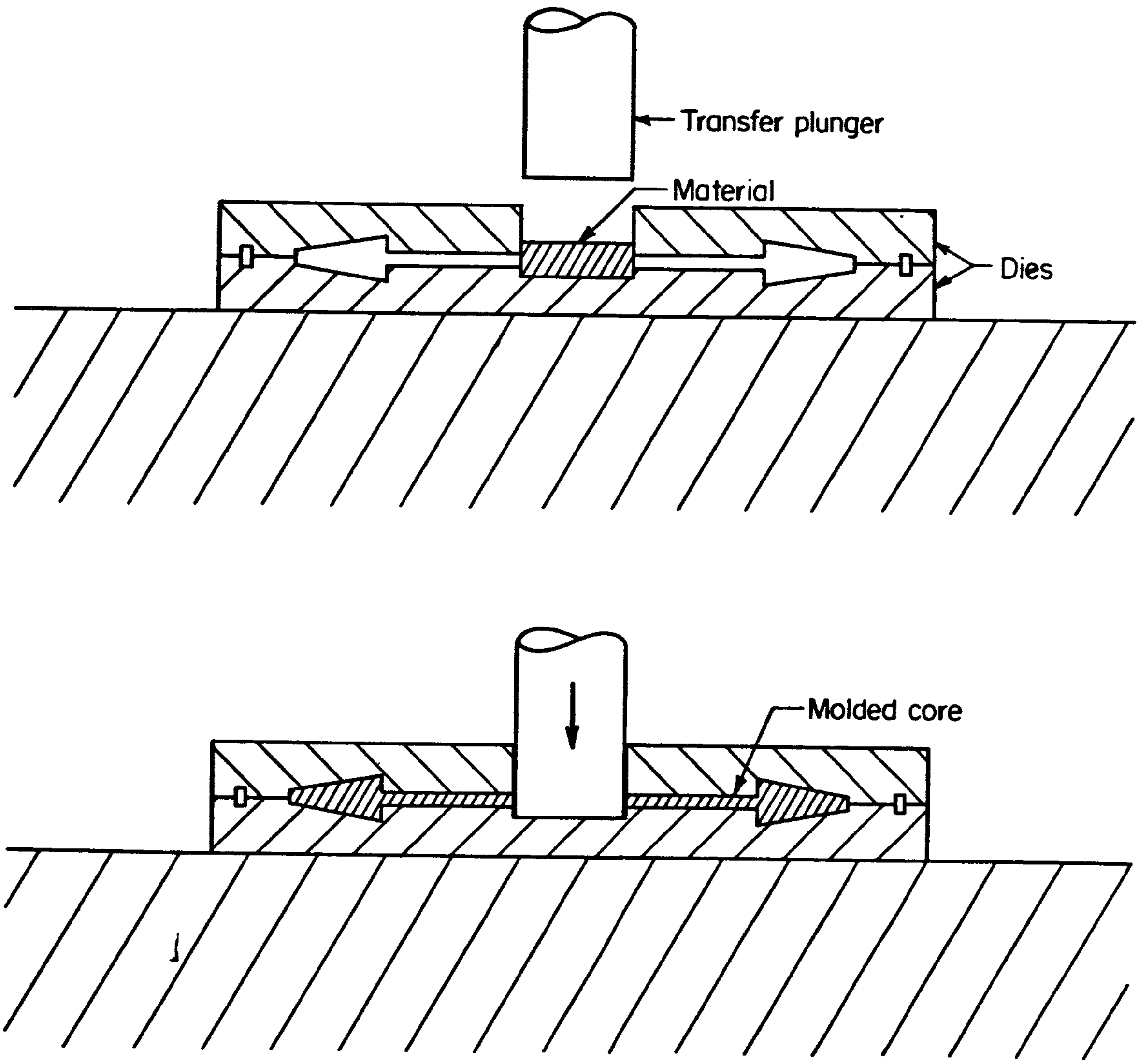


FIGURE 39. TRANSFER MOLDING OF PREFORMED CERAMIC CORES

Injection molding of Alsimag 145 (a glass-bonded silica-base ceramic manufactured by American Lava Corporation) was satisfactory for a hollow airfoil but it required curing in a mold to control warpage.[66] For uniform sections, extrusion could be used, and, if the extrusion was mold-cured, a twist could be put in. Dimensional control is difficult, however, and shrinkage is a problem. By injection molding the core with its curing (setter) block, and allowing for shrinkage in both parts, strong tapered or twisted cores could be made economically.[66] About 10-percent shrinkage was experienced in drying and firing.

Core-removal methods, in general, may involve either mechanical (sandblasting) or chemical (alkali-leaching) techniques. Alkali leaching may be accomplished by immersion in molten alkali or by pressurized (to 1000 psi) systems.[62, 65, 66] The alkali-leaching method is applicable to silica (quartz) and leachable ceramics which may be glass-bonded silicates or glass-bonded zircon. Large cores might be leached in molten-salt baths.

The cost of producing a hollow casting is directly related to the cost of the core. If, in a hollow turbine-blade casting, "posts" are to be incorporated across the cavity, the core will be less costly if the posts are parallel as illustrated in figure 40. The simple shapes shown as figures 40c and 40d are economically made by extrusion.

Mold making. – The mold must be made from a stable composition that has little or no tendency to outgas after it is placed in the vacuum furnace. Conventional sand, or organic-bonded shell molds cannot be used for vacuum casting because of their inherently high volatile material content. The present state of the art is to use the ceramic shell-molding process for making the mold, which might then be backed up with a refractory grog to prevent the preheated mold from losing heat while waiting for the pour.[76] The present practice favors unsupported shells.

Until 1958, a great number of airfoil shapes had been made with a monolithic mold, that is, a solid, more-or-less conventional mold of silica, or aluminum silicates bonded with ethyl silicate or colloidal silica. These molds were too heavy, and were not capable of producing castings with closely held dimensional tolerances. In addition, they were quite subject to cracking.[65]

For the past 10 years the shell-molding technique has become universally accepted for making both airfoil shapes and large castings. The method is based on the successive building up of layers of the refractory on the wax pattern, melting out the pattern, and firing the mold. Figure 41 shows a pattern, mold, and finished casting for an integral turbine wheel.

Many types of mold materials have been used. The principal requirements are that the mold have sufficient refractoriness and mechanical strength to resist both the room-temperature handling and the high temperatures encountered in firing, preheating, and casting; furthermore, it must not react chemically with the molten superalloys that are cast into it.

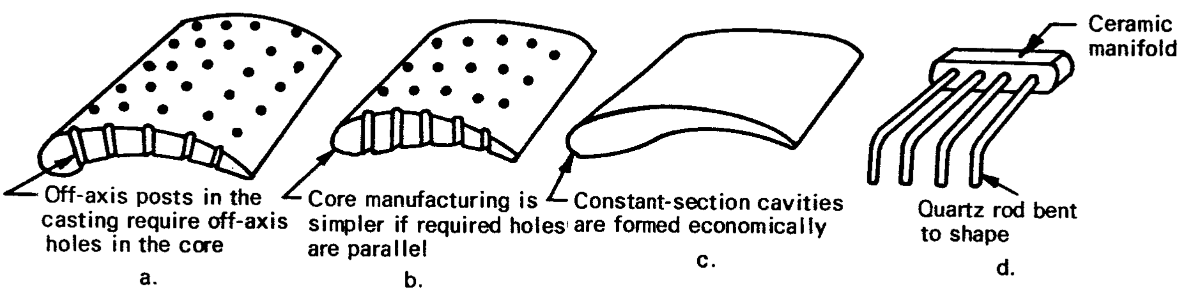


FIGURE 40. COMPLEXITY OF CORES INCREASES THE COST OF HOLLOW CASTINGS(74)

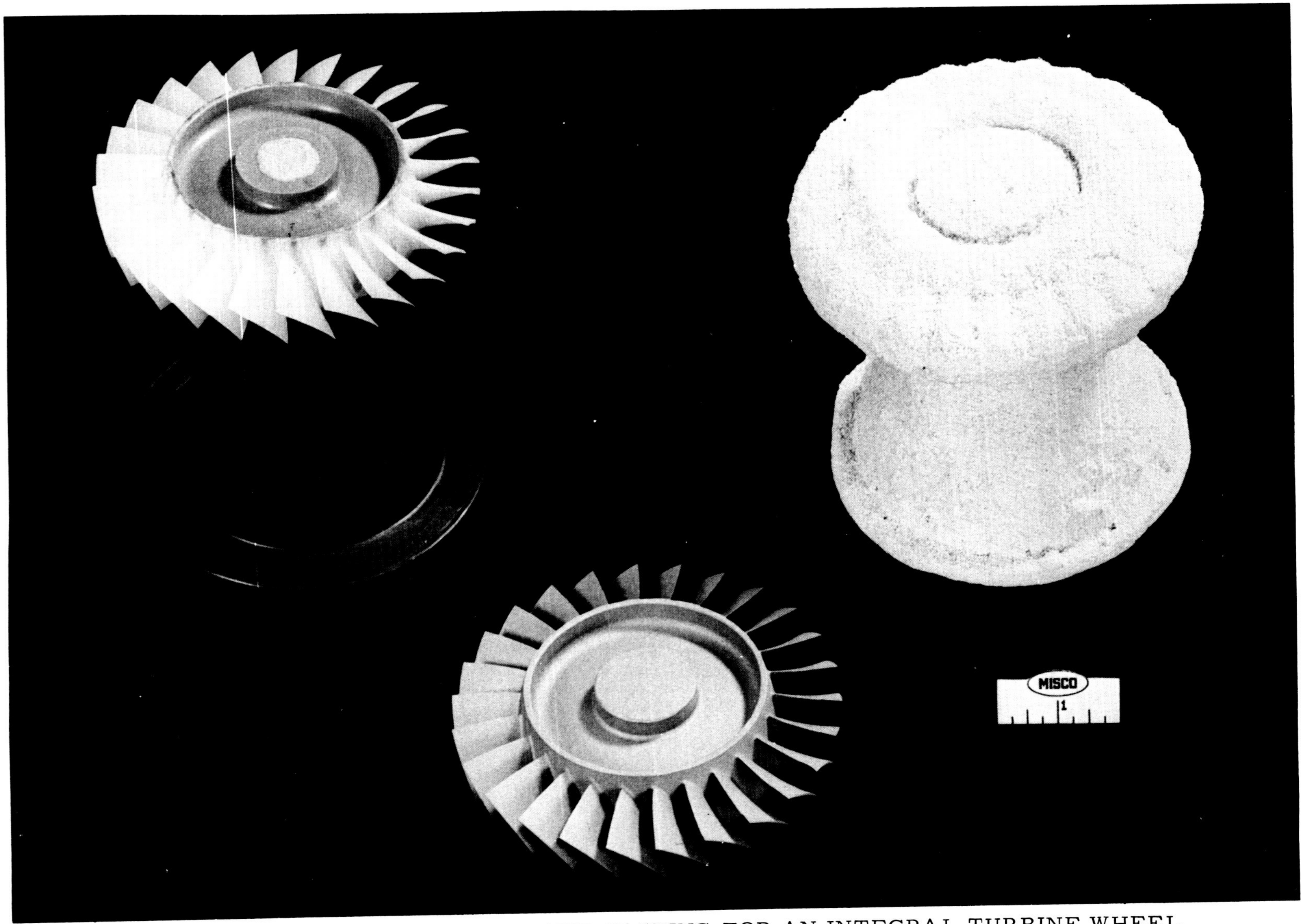


FIGURE 41. PATTERN, MOLD, AND CASTING FOR AN INTEGRAL TURBINE WHEEL

(Courtesy MISCO Division, Howmet Corporation)

A recent Air Force-sponsored program to develop methods for making large superalloy castings, made use of conventional cope-and-drag ceramic molds and also sand-faced molds.[61] Details are presented in the appropriate sections that follow.

The facecoat: The first dip coat (sometimes called the facecoat or precoat) determines the surface finish of the casting, and it obviously must be high quality and free of any tendency to spall during any of the drying or heating operations. An additive for grain-size control may be incorporated in the first coat; this additive (sometimes called an inoculant) is for nucleating grains in the molten metal next to the mold wall, thus reducing the grain size.

In the dip-coating technique, many controls must be exercised on both the materials used and on the process variables. Such factors as chemical composition, particle size, and methods of blending refractory materials are carefully prescribed. The slurry viscosity, temperature, and pH must be controlled to insure complete covering and correct thickness of the facecoat.

The primary-coating slurry may be alumina or zircon (zirconium silicate) bonded with a solution of ethyl silicate, sodium silicate, or silica sol (colloidal silica).[77, 78, 79] The most widely used mold materials today are zircon, alumina, zircon plus alumina, and fused silica with zircon; binders are usually silica sol or ethyl silicate. These mixes are adequately inert to superalloys.[80] When production schedules are such that flexibility of solidification rates is needed, ethyl silicate is attractive as a binder because, by proper control of hydrolysis and pH, the sols can be controlled to harden in 2 minutes to several hours.[67] The facecoat grain size is usually -325 mesh,[67, 75] while the outer coats may be 200 mesh.[67] Care must be taken that no ethyl silicate remains between the wax pattern and the precoat; the residual can cause violent "blows" or degassing when the hot metal hits the mold.[77]

For making large castings in a two-piece mold, it was found that fine zircon sand (168 mesh) bonded with sodium silicate (3-percent binder by weight) could be used as a facing on the cope-and-drag. It was backed by Calamo 20 sand (trademark of Harbison-Walker) bonded with pure sodium silicate. Better surface finishes were obtained when the zircon was mixed with 100-mesh calcined kyanite. The facing may be from 1/2 to 2 or 3 inches thick, depending on the location, shape, and other factors. Weight and cost are important in limiting the facecoat thickness.[61]

Cobalt oxide is a common facecoat additive for controlling the grain size of the casting by acting as a grain-nucleation agent, although its effectiveness varies with the amount of superheat in the molten metal.[61, 65, 81] (The subject of grain size and morphology is discussed further under "Melting and Casting"). Other grain-nucleating agents have been suggested as mold additives. For example, there are patents suggesting cobalt aluminate or cobalt silicate for this purpose.[82, 83] Typically, 20 to 50 grams of

cobalt aluminate or silicate would be added per liter of slurry, although up to 200 grams per liter is also said to be effective. It is theorized that the cobalt aluminate or cobalt silicate is effective because the cobalt is fully reacted with the melt during the nucleation process, whereas cobalt oxides are believed to be incompletely reacted.(82)

Another patent suggests the use of 1 to 5 percent by volume of a reducible compound (such as oxides) of iron, nickel, cobalt, or manganese.(84) Such compounds are reduced by injection of a reducing atmosphere (e.g., trichlorethylene) at the time of pouring to provide finely divided molten metal to act as nucleation agents.

In the development of methods of making large superalloy castings, cobalt oxide (with alcohol and ethyl silicate as the vehicle) was brushed on the finished mold cavity surface as a slurry.(61) Mixed cobaltous and colbatic oxides, which represent the less expensive grades, are available under the trade names "Gray Co Oxide", "Black Co Oxide", and "Metallurgical Grade Co Oxide". They were reported to be as effective as technical-grade cobalt oxide for grain refining in large castings.(61) Figure 42 shows that with 100 degrees F superheat, the mode of solidification was strongly columnar with or without a cobalt oxide mold coating. However, in plates solidified in the coated mold the width of the columnar grains is less than those from an uncoated mold.

For the usual shell molds bonded with colloidal silica, the highest purity grain-refining additives are recommended because impurities can adversely affect the stability of the slurry by neutralizing the charge on the silica particles in suspension.(85)

Efforts to incorporate a slurry of cobalt oxide in an alcohol/ethyl silicate vehicle for painting on the surface of a mold for large castings sometimes resulted in surface defects where the layer was too thick. Mixing of the cobalt oxide with the ceramic grain (2 to 5 percent by weight of ceramic grain) as is done in shell molding, resulted in severe spalling when the alcohol was being burned off the gelled mold. To avoid this, compounds of cobalt that would convert to the oxide during firing were tried as an alternative. Cobaltous carbonate, cobaltous acetate, and cobaltous nitrate were tried, but, for various reasons the results were negative.(61)

Both cobalt oxide and iron oxide have been mentioned as grain-refining additives for cobalt-base alloys. However, such inoculants are rarely used for cobalt-base superalloys because grain size is more dependent on casting variables than on grain-nucleating agents.(86)

Dipping: The slurry must be properly mixed so that no air bubbles are entrained in it and so that the ceramic is uniformly dispersed throughout. Blade-type mixers are used for this purpose. Blade size and speed are carefully chosen to prevent turbulence, settling, and overheating. Overheating is to be avoided because the carrier will evaporate too quickly and

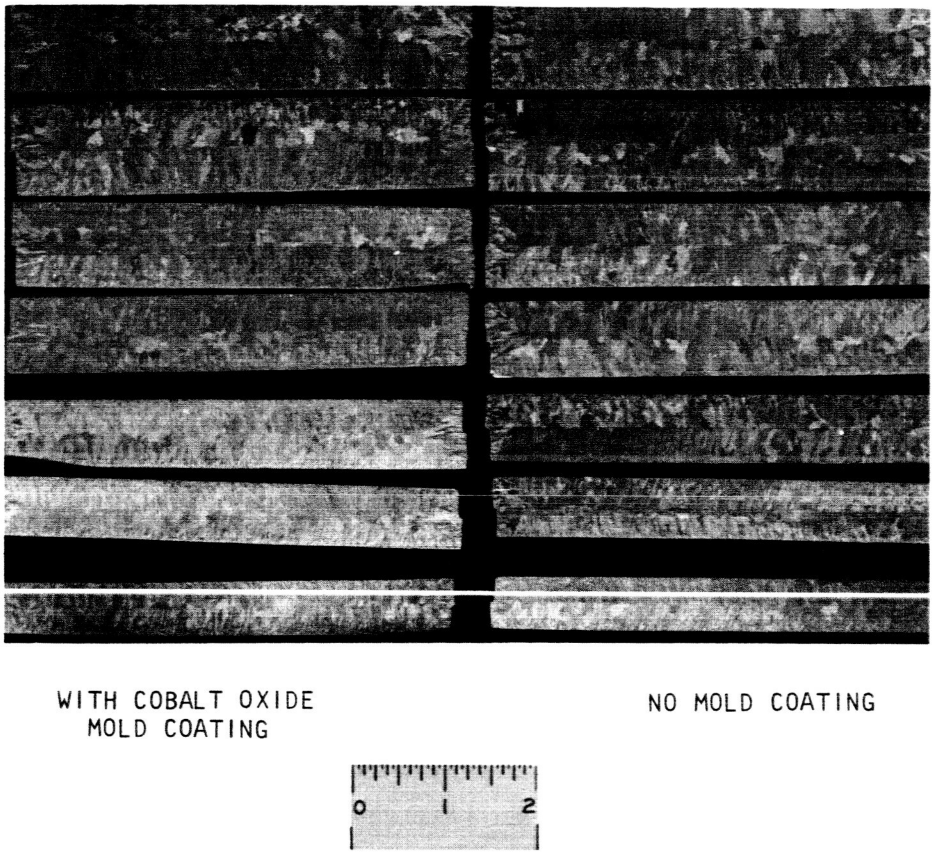


FIGURE 42. MACROETCHED SPECIMENS FROM CAST PLATE OF VARIOUS THICKNESSES OF ALLOY 713 LC, POURED AT 100 DEG F SUPERHEAT[61]

(Courtesy U. S. Air Force Materials Laboratory, Manufacturing Technology Division)

because the slurry viscosity will be changed. High slurry viscosity is desired on the first coat so that it will adhere to the smooth pattern.(67)

Air bubbles must be avoided in dipping the pattern into the slurry. One description of the method is that the "pattern must be immersed and not plunged"(67), but fast immersion and slow withdrawal by pneumatic units has also been reported.(71) Howmet reports that the first three coats are always hand dipped, except for very heavy castings. Immersion time is critical. The outer layers of a previously coated pattern must be dampened by the second dip in the slurry but not soaked, which might compromise the integrity of underlying coats. When the wet assembly is removed from the bath it is allowed to drain free of excess slurry; special care is taken to avoid excessive build-up anywhere on the surface or at joints.(67) Figure 43 illustrates hand dipping of a cluster of four turbine stator vanes. Automatic dipping is preferred in some plants because better consistency is obtained.

Stuccoing and drying: While wet, the coating on the wax pattern is stuccoed (dusted) with a coarse refractory such as 50 or 60-mesh alumina. The inner coats may be as fine as 140 mesh, or in some cases 50 to 100 mesh is preferred for the first three coats. Back-up layers can be quite coarse, 12 to 30 mesh being common. The primary purpose of the stuccoing is to provide a base for successive dips.(67) The stuccoing can be done by placing the wet mold in a shower of coarse particles from an overhead vibrating grate or by immersing it in a fluidized bed of coarse sand.(67, 80)

At one time, the mold was made of only two to four layers, backed up by loose MgO refractory in a can. The method is used by TRW Metals Division but 4 to 9 dips are typical. Better heat retention is possible than if no back-up were used. For the free-standing mold in wide use, 8 to 12 dips with drying between each dip, are not uncommon for building up the mold wall. Much depends on the kind of binder used; for example, with the ethyl silicate system used by Austenal Microcast Division of Howmet Corporation, 10 to 15 dips are used because their shell mold is weaker. This binder, a so-called "Hydrolyzed binder", consists of alcohol, ethyl silicate, water, and an acid. It has the advantage of rapid drying as the alcohol is driven off, and can be set chemically with ammonia in 5 to 6 minutes. Consequently, an automatic carousel-type dipping machine can be used (see figure 44), with stations of the cycle in the dip tank, the warming ovens, and back around again for additional dips. After the first dip, which requires 12 hours to complete, the entire process is completed in 1 or 2 additional hours.

The time to complete the mold, reported variously as 1/2 day, 1 day (most common), and up to 3 days(65) depends on the kind of mold binder being used. The drying time for colloidal silica suspensions is 2 to 5 hours, whereas for the silicate sols in ammonia, it may be only a matter of minutes.

The shell is dried in controlled-humidity ovens or cabinets (about 40-percent RH); vacuum drying is the last step if the shell is made with a water-base binder. Controlled humidity at about 50-percent RH is used for the facecoat at

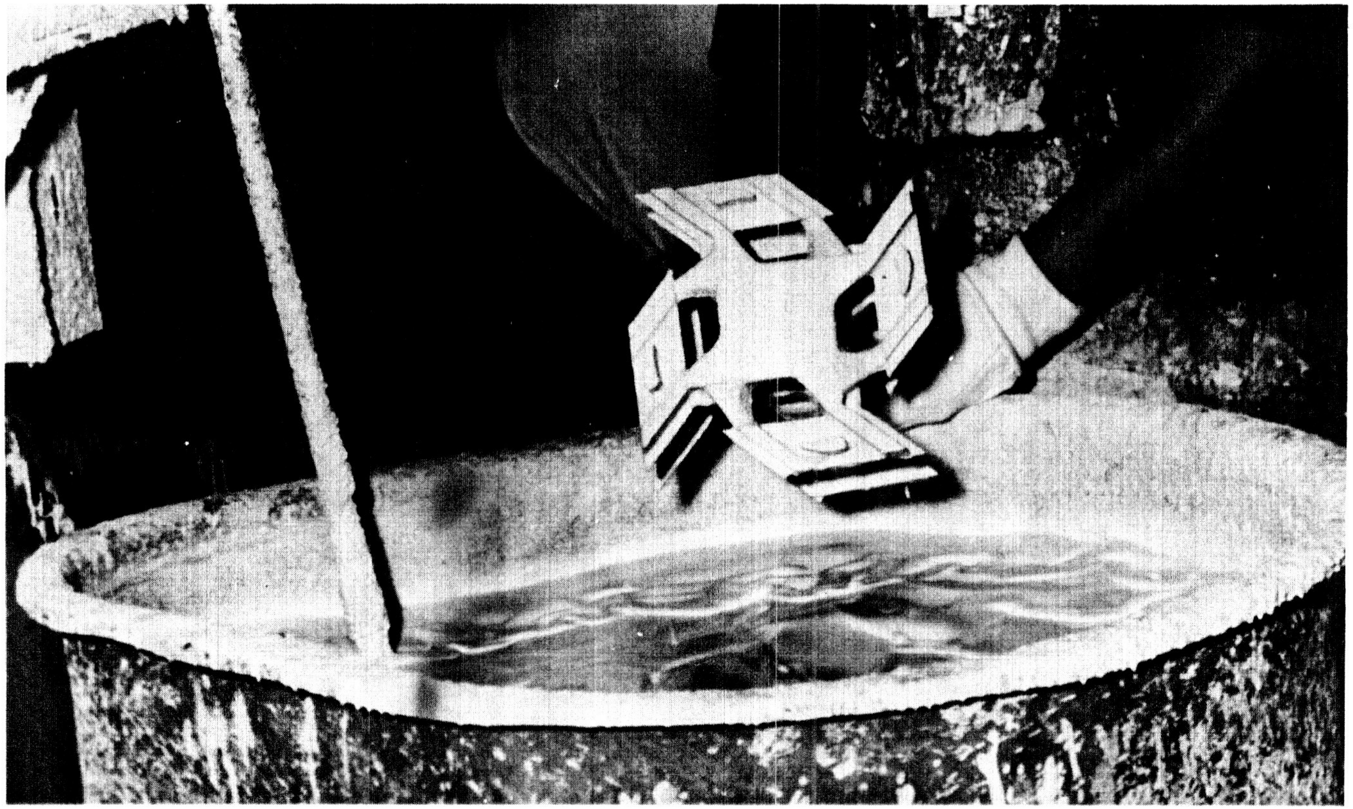


FIGURE 43. HAND DIPPING OF A PATTERN IN REFRACTORY SLURRY PRIOR TO ANOTHER STUCCO COAT

(Courtesy TRW Metals Division)



FIGURE 44. CAROUSEL TYPE DIPPING, STUCCOING, AND DRYING MACHINE

Austenal, and 25-to 40-percent RH for the back-up coats. For water-base binders the ideal drying condition is to have the wet-bulb temperature equal to the ambient temperature of the dipping room. This eliminates problems that may arise from unequal expansion of the wax pattern and the shell. Each succeeding layer may be of a different composition and grain size, but when the process is complete the shell thickness is from 1/4 to 1/2 inch for the airfoil-type castings. Figure 45 shows a completed mold for a prototype of a large aircraft structure part.(87)

Dewaxing: When the mold has been dried, it is ready for melting out (dewaxing) of the wax pattern. Various methods have been used for accomplishing pattern removal.(62, 71, 73, 78, 88) Examples include steam autoclaves, solvents, "shock heating" (flash dewax), conduction through the mold refractory, hot sand, and burning. Concerning these alternatives, solvent removal was at one time considered because of its ability to remove the wax without stressing the mold, which can occur if the wax is heated and does not flow out immediately. It is an expensive method, however. The dangers of stressing the mold by wax expansion are avoided by shock heating, which is accomplished by lowering the mold into a furnace at about 1800 to 1850 F; this quickly melts the wax next to the mold, which allows for expansion.(60,73) The conducted-heat method uses high-frequency induction to heat the mold, and can operate at lower temperatures than the shock-heating method, but it has sufficient other drawbacks to limit its practicality. In the hot-sand method, the mold is placed in a box, and fine, hot sand is dumped into the box to bury the mold. Complete wax pattern removal is accomplished in 10 to 20 seconds.(71) The steam-autoclave method has the advantage of not subjecting the wax and shell to such severe thermal gradients as the shock-heating method because the steam permeates the refractory mold material and heats the wax more quickly than in the shock-heating method.

In dewaxing by burning out the wax, the mold and pattern are inverted over a gas burner, which ignites the wax. After about 15 to 20 minutes the wax has been burned out, and the mold is further burned out for 6 to 10 hours, with the latter step also serving as a preheat prior to casting.

Plastics, because they have higher melting points than waxes, are more difficult to remove. Also, since they are heated over a wider temperature range before melting, they expand more than waxes (5-10 percent for waxes versus 19 percent or more for plastics)(67). The danger of cracking the mold during "dewaxing" of plastics is therefore greater than for waxes.

Ordinarily, the shock heating, wax liquation occurs in 10 to 20 seconds at the mold/wax interface, and complete removal is accomplished in 3 to 4 minutes(67), although 2 to 3 hours is usual for assuring that no carbon residue remains. If the wax is to be saved, the mold may be moved to a cooler furnace after liquation, so that the wax will not be burned. However, an oxidizing atmosphere is important so that all traces of the wax are removed

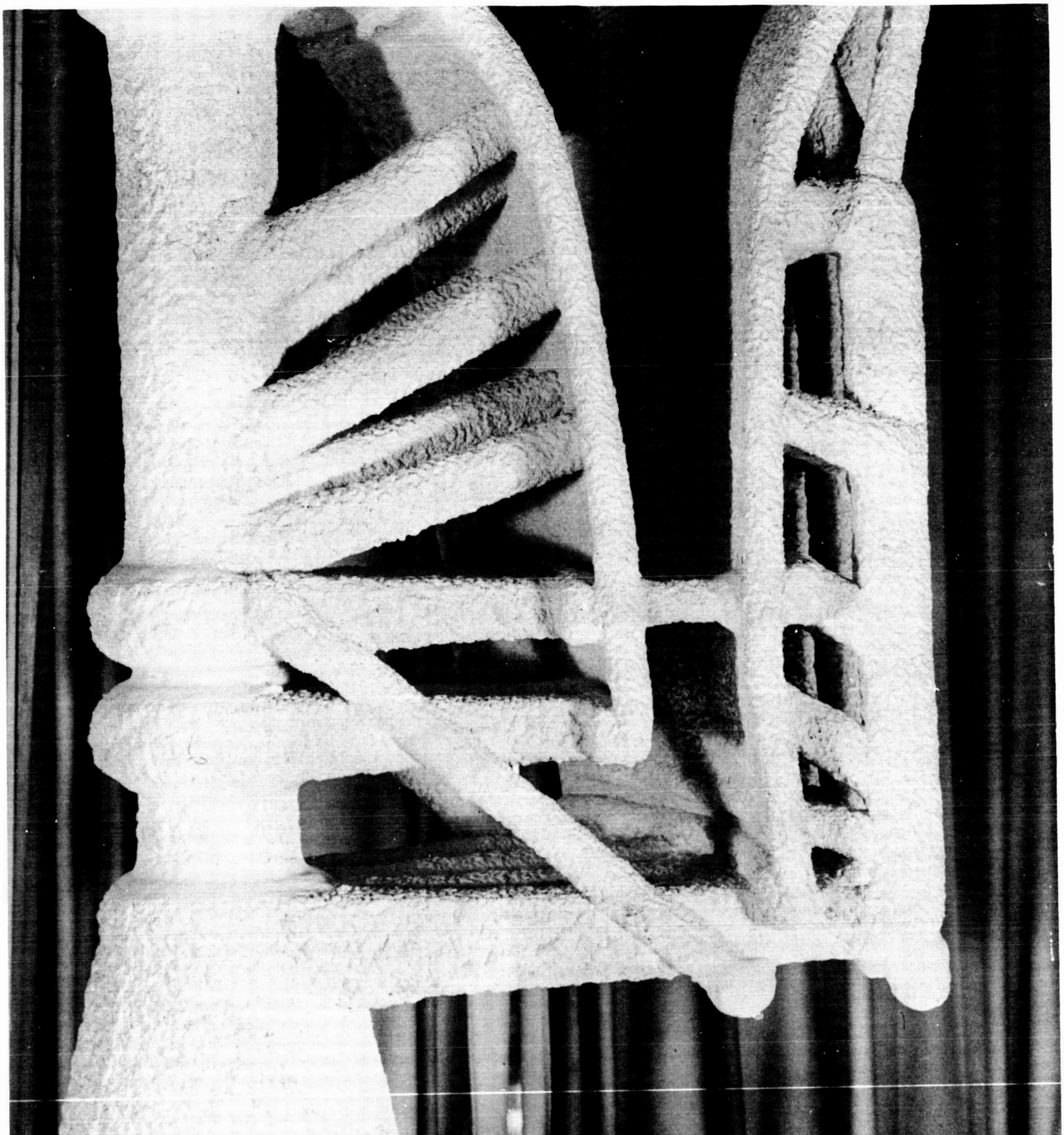


FIGURE 45. COMPLETED MOLD FOR PROTOTYPE OF A LARGE AIRCRAFT STRUCTURAL COSTING

(Courtesy TRW Metals Division)

and there is no carbon residue.[67] Figure 46 shows several molds being removed from the furnace after dewaxing. A completed mold is shown in figure 47.

After flash dewaxing or steam-autoclave dewaxing, the mold may be inspected, cleaned with a vacuum cleaner, and capped off with aluminum foil or other protective covering while awaiting the preheating furnace.

Firing and preheating the mold: When the investment mold has been dewaxed, it is fired, an operation that also serves as the preheating step prior to filling it with molten alloy. Almost all casting waxes have an ash content below 0.05 percent, which consists almost entirely of the oxides of calcium or magnesium. It does not affect the casting.[64] If the mold is not backed up with loose refractory, supplementary localized insulation might be used in order to overcome hot tearing, grain size, or porosity problems. The mold preheat temperature affects the ability of the metal to fill the fine details, but it can also affect the grain structure and soundness of the casting. Thus, the specific preheating temperature must be chosen according to the requirements of each casting.[78] A typical firing (preheating) temperature for nickel-base superalloys would be between 1800 and 1900 F for 2 hours[71]; 1900 F is a typical temperature for cobalt-base superalloys.[86]

For rammed sand molds bonded with sodium silicate (zircon sand facing Calamo 20 backing), it was found that baking above 800 F is required (perhaps 1000 F is a practical level).[61]

Melting and Casting

Typical production cycle[62, 65, 66, 76, 78, 80, 89]. – Historically, the various vacuum-melting and casting schemes that have been used include indirect-arc and induction type melting furnaces, and for casting, the Durville and other roll-over methods wherein the upside-down mold is attached to the melting furnace. Today, however, the two-chamber, semicontinuous system is becoming the standard in the industry.

The two-chamber system shown schematically in figure 48 consists of a melting chamber (with a charging lock) and a mold chamber; the two chambers are separated by a pneumatically operated flapper door. This arrangement permits the melting chamber to remain under vacuum continuously. The mold chamber can be either underneath the melting chamber (as in figure 48) or alongside it (as shown in figure 49).

The procedure for a typical cycle is as follows:

(1) With the vacuum already established, place the prealloyed ingot in the charging crucible through the charging lock and turn on the power.

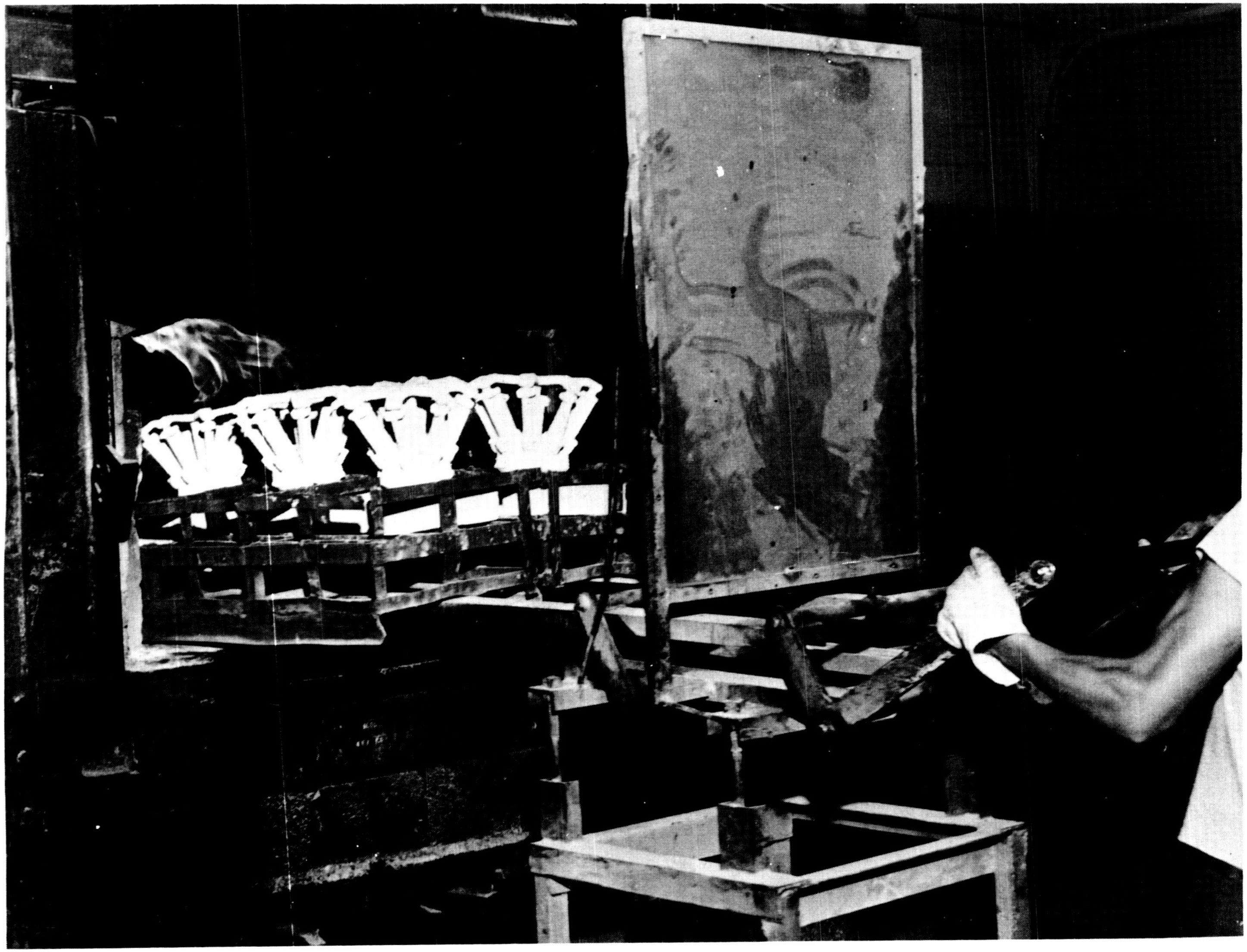


FIGURE 46. MOLDS BEING PULLED FROM FURNACE AFTER DEWAXING

(Courtesy TRW Metals Division)

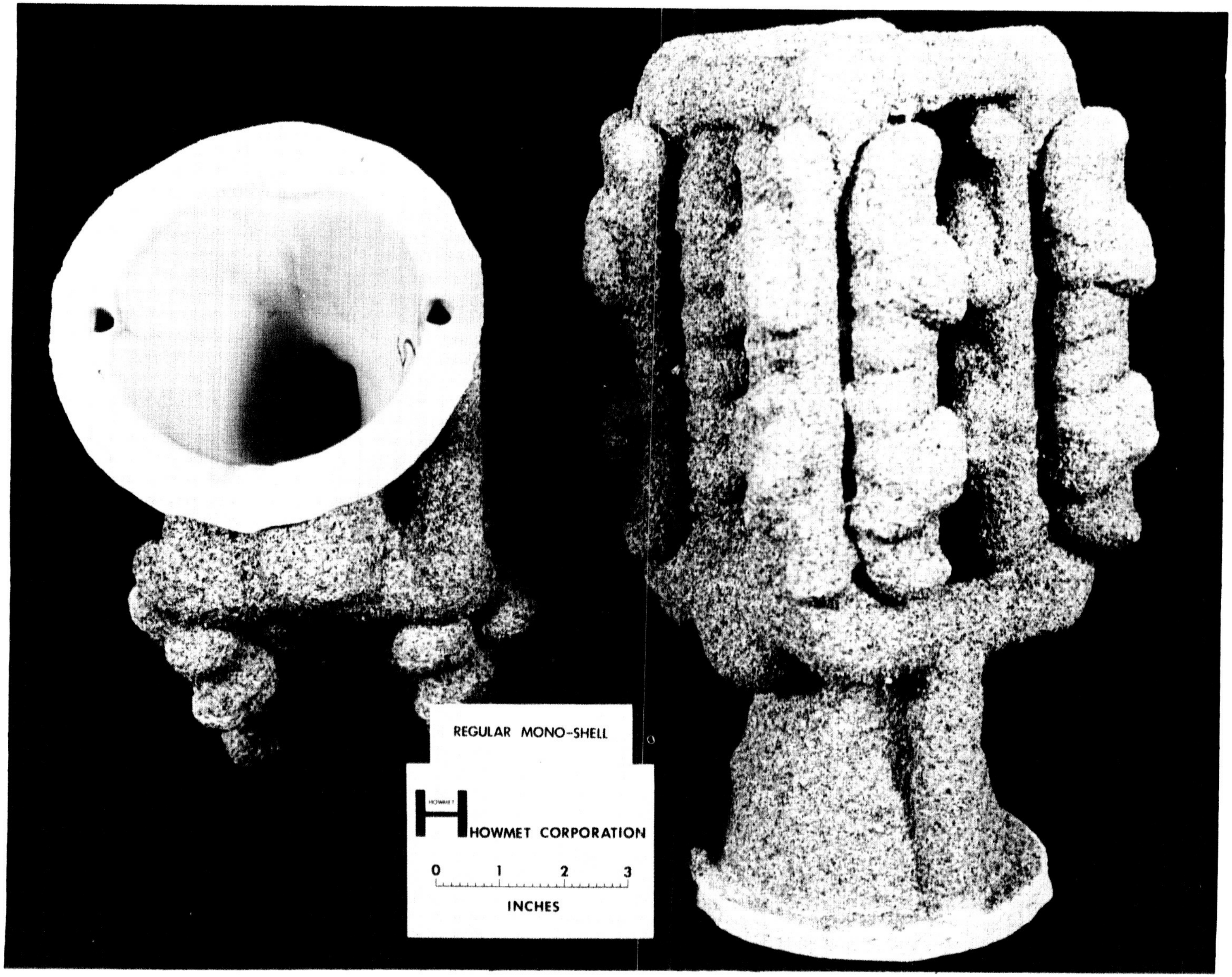


FIGURE 47. COMPLETED MOLD MADE BY THE MISCO MONO-SHELL PROCESS

(Courtesy Howmet Corporation)

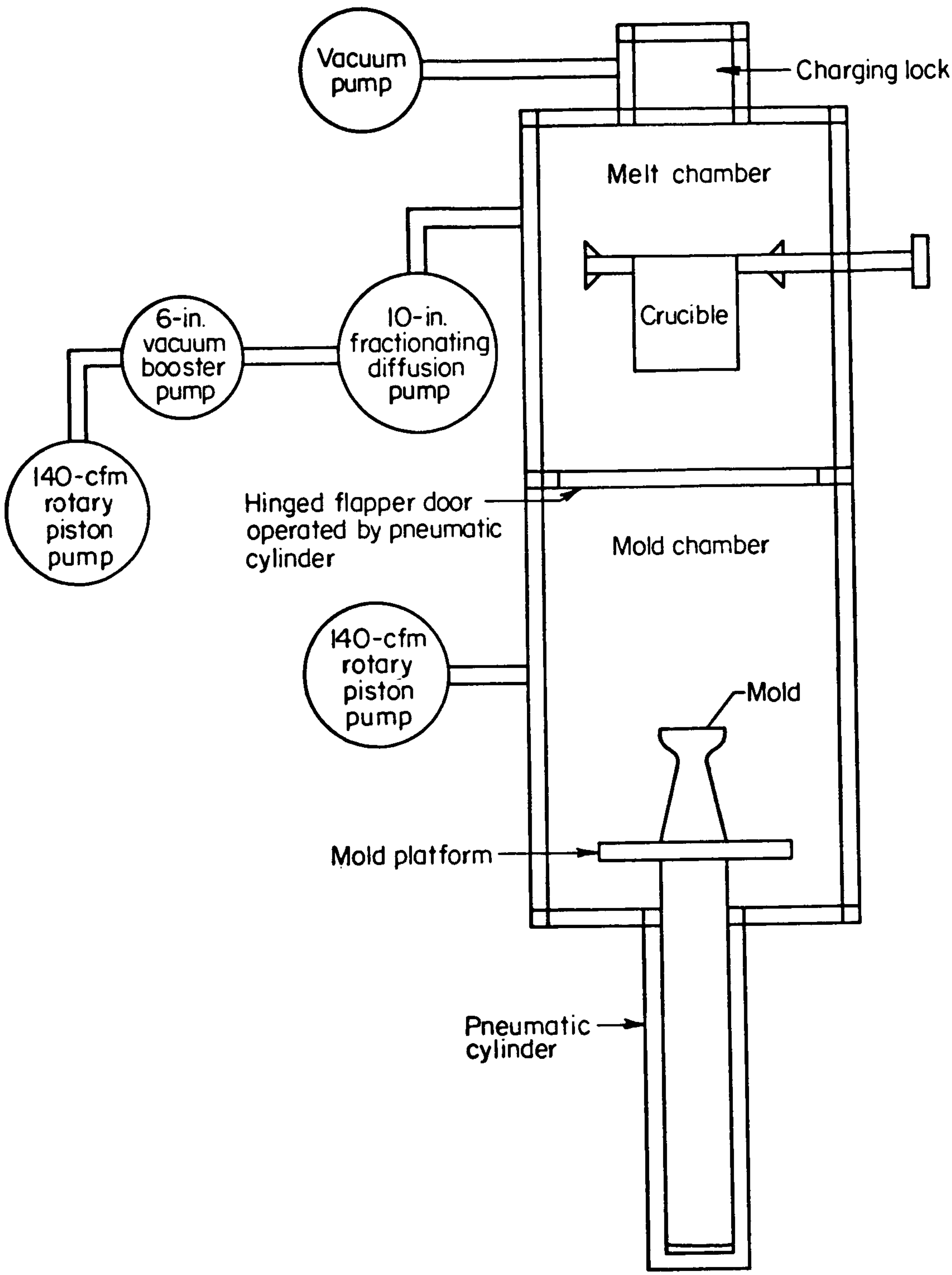


FIGURE 48. SCHEMATIC OF TWO-CHAMBER VACUUM-CASTING SYSTEM

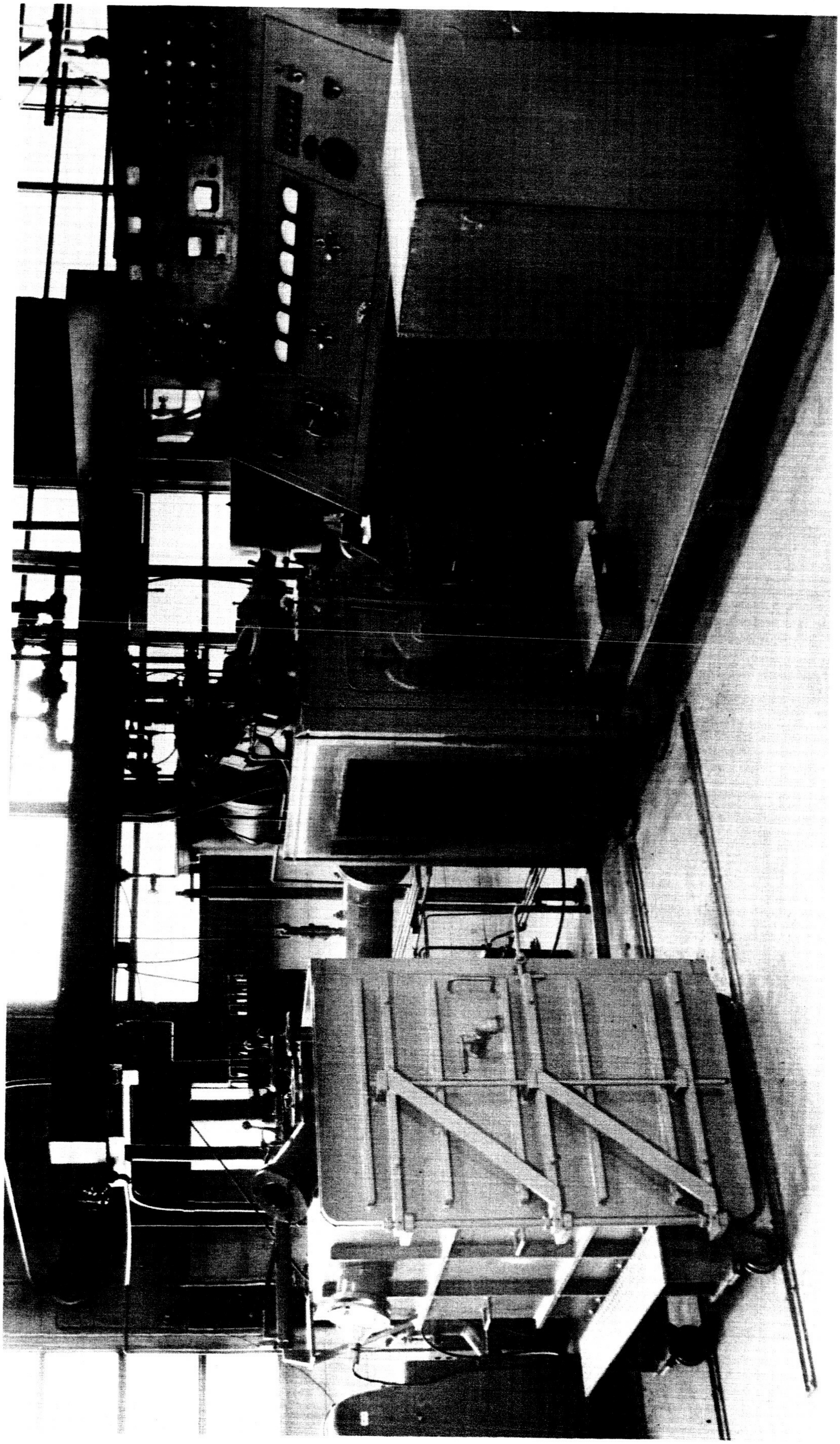


FIGURE 49. VACUUM CASTING UNIT WITH MOLD CHAMBER ALONGSIDE THE MELTING CHAMBER, SHOWN SEPARATED

(Courtesy Austenal Microcast Division, Howmet Corporation)

(2) While maintaining a high vacuum (0.1 to 1 micron)* in the melt chamber, place the preheated mold on the mold-chamber platform, close the door, and pump the mold chamber down to perhaps 50 to 100 microns.

(3) When the melt is ready, open the flapper door between the chambers and move the mold platform into the pouring position in the melt chamber. The pressure will increase, but should be quickly lowered to under 1 micron by the high-vacuum pump.

(4) Pour the heat quickly, move the mold to the mold chamber, close the flapper valve, and start recharging the crucible.

(5) Open the mold chamber, remove the mold, and get ready for the next cycle.

If a single-chamber furnace is used, the cycle time is much longer. In this case the mold must be the backed-up type in a can so that the preheat temperature can be maintained while the chamber is being pumped down in readiness for melting and pouring.

Furnaces and auxiliary equipment. – The most common vacuum-casting furnaces are single-mold units. They cast one mold at a time from a melt that usually weighs 20 pounds or less[65, 76, 89], although melts of 25 pounds are common and melts for large superalloy castings weighing 100 pounds or more are being increasingly required.[65] A furnace with a 1000-pound melt capability has been announced, and the eventual rating is said to be 3000 pounds.[90]

In typical production cycles, 10-to 12-pound charges can be melted and poured in 5 to 6 minutes, which result in overall rates of 6 to 10 fills per hour.[65, 76] Newer facilities, utilizing a 150-kw power source can melt a 20-pound heat every 2-1/2 minutes and complete a cycle in only 6 minutes.[89]

Vacuum pumps: In the early days of vacuum casting (during the late 1950's and early 1960's), high-vacuum oil-vapor booster pumps (3500 cfm) backed by rotary-piston mechanical pumps were commonly used to provide a vacuum of 5 to 15 microns during melting. Addition of a vapor-diffusion pump between the melt chamber and the vacuum booster permits the entire process to be conducted at 0.1 to 1 micron,, and this has become standard today.[76, 89] High pumping capacity is important from the standpoint of superalloy quality as well as production rates. Though there is some disagreement regarding the ultimate pressure required, today's higher pumping capacity allows production rates to be maintained at very high vacuum, so that the argument is perhaps irrelavent. A 9-foot-diameter melting chamber, for example, can be pumped down in only 15 minutes.[90]

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* 1 micron = 10^{-3} torr.

Even so, it is well to recognize that in earlier vacuum casting 15 microns was considered to be sufficient(76), but 0.1 to 1 micron has become today's criterion for proper melting conditions.(65) Certain foundries(77) considered 1 micron to be the maximum pressure, even in the early days. Some have considered high vacuum to be overemphasized, however, and in a Durville-type furnace (in which the mold is attached upside down to the furnace and the whole assembly is rotated 180 degrees to fill the mold) a pressure of 1/2-mm Hg was said to be a satisfactory vacuum level; at 10 degrees before the vertical, argon backfilling helps to force the melt into the mold.(91)

According to one authority(80), most vacuum casters believe that the vacuum should be under 1 micron, "so that is where we operate". In normal production, at the time of pour, the vacuum on a small furnace may be 3 to 4 microns, and on a big furnace 40 microns.

The same source reported that IN 100 and alloys like it had been intentionally melted at a level of 100 to 200 microns without any effect on the normally measured mechanical properties.(80) On the other hand, when the vacuum on a heat of B-1900 had been broken for 15 to 20 minutes, gas pickup and slagging was the result.

Leak-up rate:* There is good agreement that leak-up rate is more significant than vacuum level. A large vacuum pump on a leaky furnace can keep the vacuum level low, even though relatively large volumes of air are brought in. Proper limits for leak-up rate must be established for each furnace. It is difficult to specify them beforehand as the criterion is whether a good casting can be produced.

Cold leak-up measures the actual leakage in the furnace through the various ports, locks, and other openings. A value of 60 microns per cubic foot per minute for a typical two-chamber apparatus has been reported as satisfactory.(76) The hot leak-up rate measure, in addition to leakage, the amount of outgassing from all the components in the furnace as well as from the molten metal. Rates of 600 to 1200 microns per cubic foot per minute are said to be tolerable.(76) A hot leak-up of 8 microns in 15 seconds for a "small furnace", 5 microns in 1 minute for a "larger furnace", and 5 microns in 30 seconds for a larger furnace when the metal is "percolating" (outgassing vigorously) have also been reported.(80) Table 12 shows the relationship of certain elements to furnace-vacuum characteristics in melting MAR-M 200 and directionally solidifying it.(92) The oxygen content was believed to increase as a result of reaction with the furnace lining. These figures can serve as guidelines, but cannot substitute for actual experiments on other pieces of equipment.

These gas contents are extremely low and they represent results on a research furnace. In practice, hydrogen levels of master heats may be higher by a factor of 2 or 3, nitrogen by a factor of perhaps 50 to 100, and oxygen by

* A term used in the industry to denote rate of rise of the pressure in the sealed furnace with the pumps shut off.

a factor of 20 or more. A great deal depends on the ratio of virgin material to revert, the number of remelts, and the furnace operating conditions.

TABLE 12. EFFECT OF VACUUM-FURNACE CHARACTERISTICS ON THE CONTENT OF CERTAIN ELEMENTS IN MAR-M 200 CAST FROM IDENTICAL MASTER INGOTS[92]

Vacuum-Furnace Conditions		Ppm			Wt. %		Volume Percent Voids
Leak-Up Rate, microns/minute	Working Pressure, microns	O_2	N_2	H_2	S	Si	
0.1	0.5	1.1	1.3	0.2	21	0.047	0.2
1.6	1	1.7	2.4	0.5	39	0.054	0.3
1.6	>2	1.6	1.7	0.5	44	0.066	0.4
Master Heat		0.4	1.4	0.3	52	0.066	

Crucibles: Most of the major vacuum casters use commercially-made prefired (monolithic) alumina or stabilized-zirconia crucibles. At one major casting plant, stabilized zirconia is preferred when a continuous vacuum is maintained, and 88 percent Al_2O_3/11 percent SiO_2 is used when the operation is intermittent.[75] Stabilized zirconia is preferred for cobalt-base superalloys.[86] Magnesia is still used by some manufactures for certain alloys.

Zirconia in its unstabilized form changes from the monoclinic crystal form to the tetragonal form at high temperatures, with about a 9-percent volume change in the process. Therefore, a cubic structure, stable at low and high temperature is induced by an additive; this process is called "stabilization"[93]. Common stabilizers of zirconia for crucibles are 4 percent of either CaO or MgO, although a typical composition would contain 3.5-percent CaO and 0.5-percent MgO[75]. Prolonged heating of MgO-stabilized ZrO_2 has been reported to cause destabilization to the original form.[93]

Magnesia (MgO) was at one time used extensively[65, 76, 77, 80], as was high-purity alumina[65, 75, 76, 77]. The latter seems especially suitable for rammed crucibles[77], but this usually means those used in larger furnaces that melt perhaps 100 pounds or more. Prefired alumina is subject to thermal cycling fatigue and, hence, is not usually used.

Other crucible materials have been tried, or considered. For example, prefired complex aluminum silicates and zirconium silicates, which have been used in ordinary investment casting, were investigated, but they did not resist corrosive attack at the molten-metal temperatures used for the superalloys.[65] Sillimanite (an aluminum silicate) is said to be strong, but slagging begins to occur when the temperature exceeds ≈2900 F.[77] Thoria and

beryllia, while attractive from a chemical stability viewpoint, have been ruled out because of their high cost, low tolerance for handling under normal foundry conditions, and susceptibility to cracking due to cyclic thermal stresses in melting. MgO and zirconia, on the other hand, have proven successful because of their resistance to surface erosion and accompanying low wettability, and their resistance to cracking and spalling.(65)

Installation of the crucibles is accomplished without removing the induction coil from the vacuum chamber, using a dry unbonded backup of 66-percent MgO/25-percent Al_2O_3/6-percent SiO_2 material and an alumina-cement cap. A full wash heat of a high-nickel alloy at about 3000 F is required for zirconia crucibles.(75)

The life of crucibles varies, but, for the small 20-pound units using monolithic prefired crucibles, the average life has been reported as 50 to 60 melts, with 200 occurring "with surprising frequency".(65) For practical reasons, the crucible may be changed at the end of every 8-hour shift in production (usually 48 heats), but this depends on the production cycles and whether the plant operates on a 1-, 2-, or 3-shift basis. Another report states that zirconia crucibles will last for 60 to 100 melts if the vacuum is continuous and the temperature cycles are minimized.(75) Intermittent vacuum conditions with wide temperature cycles yield lives of 20 to 35 melts for the alumina (88-percent Al_2O_3/11-percent SiO_2) crucibles. An average life of 140 melts has been reported for an Al_2O_3 crucible (with 5-6 percent SiO_2 from the binder) used for melting a Ni-Cr-W-Al alloy.(77)

Crucible life is shortened when metal oxides, formed during a vacuum break or introduced with the alloy, allow the melt to wet the crucible and penetrate its pores. Thus, the use of air locks for charging has extended crucible life by permitting a continuous vacuum. Furthermore, air locks permit the crucible to be charged immediately after the melt has been poured thereby narrowing the thermal-cycle range and reducing the stresses on the crucible.(75)

Erosion is also minimized by completely draining the crucible to avoid solidification of metal on the pouring lip and the consequent metal penetration and unequal thermal expansion between the metal and crucible refractory.(75)

Melting and pouring. Composition control: The charge material for making vacuum investment castings is typically a 3-1/2-inch-diameter bar of a master heat that has been previously vacuum-melted and cast. As a rule, no additions are allowed, whether alloying of master-heat materials or revert material (gates, sprues, rejected castings, or the like). Because no refining of the master heat is possible, except perhaps with respect to sulfur and silicon(92), precautions must be taken to minimize contamination during the remelting. The rate of evaculation is usually high enough that heating can be commenced at the same time that pump down is started.(77)

Obviously the chemical composition of the master heat should be checked to see that it conforms to the specification. If it does, no significant change in composition will occur in the ordinarily short production remelting. An example of the effect of vacuum remelting in an Al_2O_3/5-6 percent SiO_2 crucible on the composition of a nickel-base superalloy was given as the following, for a 15-minute cycle at 1-micron vacuum level.[77]:

Nominal Composition, percent	Change
C 0.15	-0.02
Si 0.20	Slight gain
Cr 15.0	Negligible
Zr 0.07	-0.008
Ti 4.0	-0.20
Al 4.0	-0.14
Co 18.0	Nil
Mo 8.0	0.20

The main problem in holding the heat for a long time would be in the evaporation of chromium and manganese (which is not given above). The negligible loss of chromium poses no problem, and since manganese, which is more volatile, is usually specified as a certain maximum value, its loss is of no consequence.

Gases in the nickel-alloy melting stock may be responsible for porosity. If the master heat is high in hydrogen it is almost impossible to remove it, even with prolonged pumping, because it is held by the titanium and aluminum. Likewise, oxygen and nitrogen levels cannot be reduced by holding the heat for a long time under high vacuum. Instead, the chromium will be boiled out.[80]

In order to keep the melt clean (free of dross) and the casting free of oxide inclusions, the original charge material should be free of primary pipe, oxide skins, laps, and refractory inclusions. Oxides and other defects from these sources are easier to avoid than to get rid of.[65,80]

Pouring and grain-size control: When the correct pouring temperature is reached and the mold is in position, the melt should be poured rapidly, the mold table moved out, and the flapper door closed so that another cycle can be started.[65] The mold is removed from the mold chamber and an exothermic mix poured on top to help feeding while the casting solidifies.

Rapidity of pouring of the melt is important in order to fill thin sections of the mold and to control grain size. Crucible "turnover" speeds of under 1 second are normal for heats under 30 pounds[77], and a typical pouring rate might be 15 to 20 pounds per second.[91] The manual skill of the operator is very important here, not only to empty the crucible quickly, but to see that

the mold is accurately lined up with the stream and that no specks of dust or refractory have fallen into the mold.(80) At Austenal, pouring is done hydraulically, and the tendency is towards mechanized pouring in order to eliminate operator differences. TRW accomplishes accurate pouring control with an automatic system known as "Mechapour", which significantly reduced variations among operators.

The pouring temperature, that is, the degree of superheat, is selected to give a good mold fill, but is must not be so high as to cause a large grain size, shrinkage porosity, or hot tearing. The melting ranges (solidus to liquidus) of some superalloys are presented in table 13. One source claims that if the gating system has been properly designed a superheat (number of degrees of temperature above the liquidus) of only 27 to 36 degrees F is satisfactory because the increased temperature does not greatly increase the true fluidity; however, the general practice is to use between 100 and 250 degrees F superheat. In this connection, it is well to note again that the mold preheat temperature is important in insuring complete filling of all details. Without additional insulation, it is important to keep the mold temperature within specified limits by controlling the time to move the mold from the preheat furnace to the mold platform, and to complete the pour quickly.

Too little superheat means incomplete filling (misruns), but even if the mold is completely filled, microporosity might be more prevalent in large castings at low superheat levels.(77) Generally speaking, the pouring temperature must be fixed on the basis of the alloy and the casting configuration.

Mold Preheat Temperature, F	Grain Structure
1000	Fine, equiaxed
1200	Onset of columnar
1400	Completely columnar
1900	Nearly equiaxed, coarser than at 1000 F

Creep-rupture properties at 1800 F were most consistent and generally better with the larger equiaxed grains than with the finer; specimens with columnar grains were inconsistent. The 1400 F properties of all-equiaxed-grain castings were more consistent than, and superior to, those having columnar grains.(67)

Cobalt-base superalloys are normally molten in the vicinity of 2450 F. Experiments on MAR-M 509 with 275 to 400 degrees F superheat using a constant mold preheat temperature of 1900 F showed that the grain size and minimum creep rate were strongly affected by the amount of superheat, and the average rupture life at 2000 F/8000 psi increased from about 70 to over 100 hours with increasing superheat. Figure 50 illustrates the data. Because of increased mold attack at the higher temperature, however, the superheat in cobalt-base superalloys is maintained at about 300 F.(86)

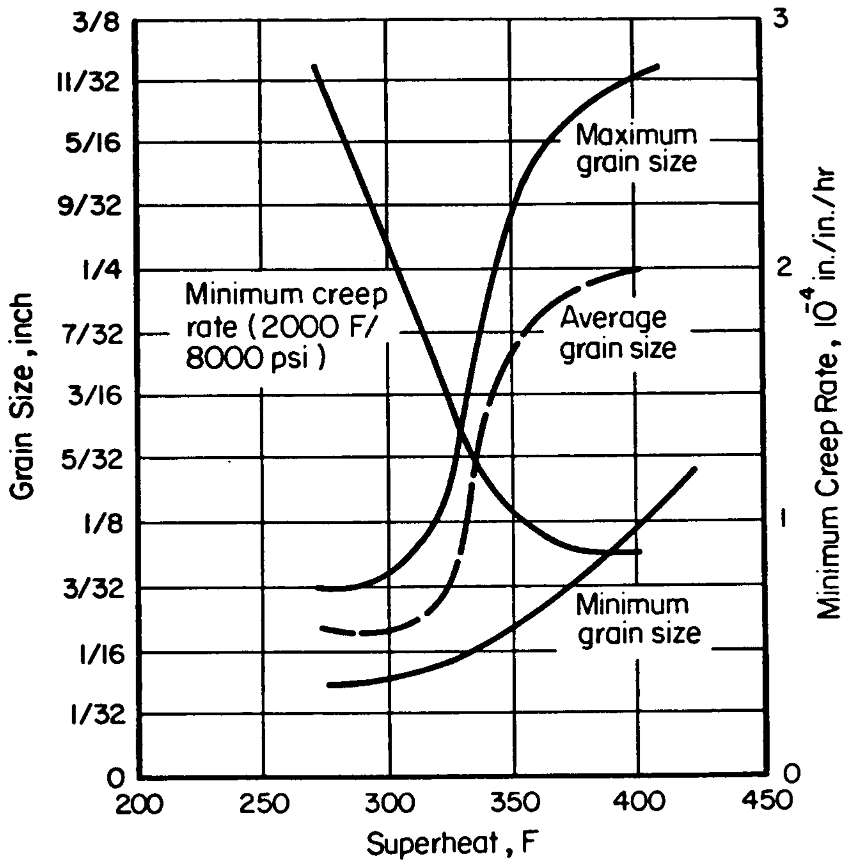


FIGURE 50. EFFECT OF SUPERHEAT ON GRAIN SIZE AND MINIMUM CREEP RATE OF MAR-M 509[86]

TABLE 13. APPROXIMATE MELTING RANGES OF SOME VACUUM-MELTED SUPERALLOYS

Alloy	Melting Range, F
AiResist 13	2400-2500
AiResist 215	2400-2500
Alloy 713C	2300-2350
Alloy 713LC	2350-2410
B-1900	2325-2375
IN 100	2305-2435
MAR-M 200	2400-2500
MAR-M 211	2350-2450
MAR-M 246	2400-2450
MAR-M 302	2400-2450
MAR-M 509	2450-2550
Nimocast 258	2390 (liquidus)
PDRL 162	2330-2380
TAX- 8 series	2450 (liquidus)
TRW 1900	2400-2450

Another way of controlling grain size is by melt temperature reduction just before pouring, followed by a quick reheating.[94] When an equiaxed structure is desired, mold nucleation agents are only partially effective. Essentially, such agents provide a small columnar grain size, which may appear as equiaxed grains on the casting surface. However, they are in reality the bases of columnar grains growing inward from the surface.

The relationship of grain size to the degree of superheat, or pouring temperature, is shown qualitatively in figure 51. Similar curves are obtained for mold preheat temperature.

The most important aspect of the graph is that the grain-refining additive is effective only in an intermediate temperature range, whereas at high- and low-superheat values the grain size is almost the same as without the additive.[65] This can become a problem in the casting of intricate parts because the higher pouring temperature may be needed in order to get a good fill, but the larger grain size that results may be detrimental to properties, particularly in the range of 1200 to 1600 F. In turbine wheels/blades,

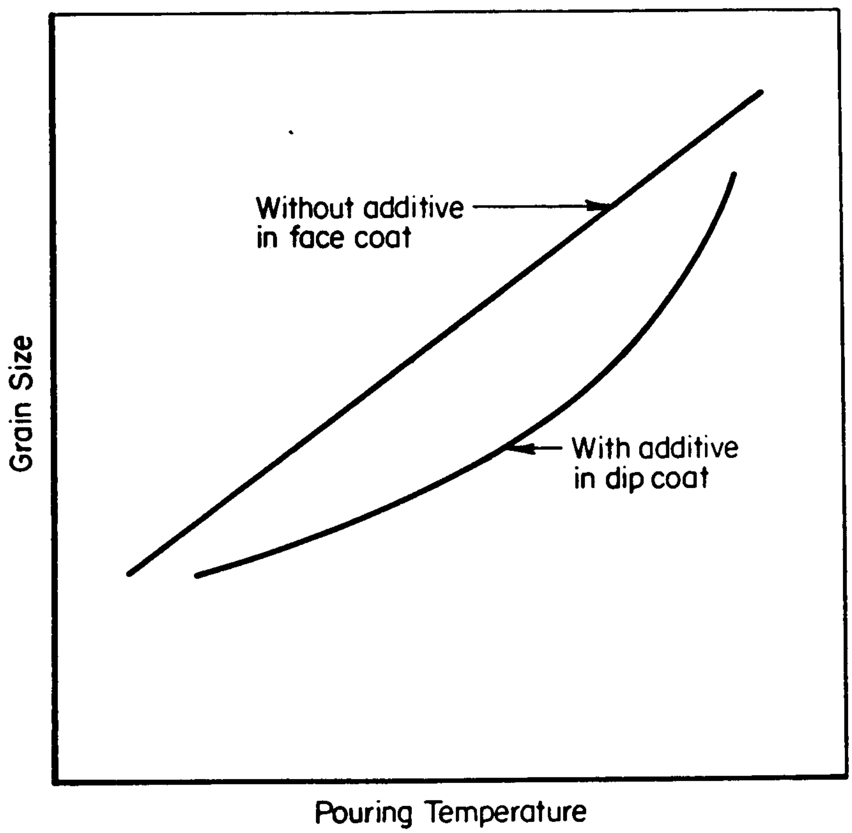


FIGURE 51. QUALITATIVE RELATIONSHIP OF GRAIN SIZE TO POURING TEMPERATURE[65]

wherein the center operates at low temperatures, ductility and strength are important. To improve intermediate temperature ductility, alloys such as Alloy 713 LC and MAR-M 246 were developed. Good combinations of strength and ductility over a wide range are also found in IN 100 and MAR-M 432. The foundry practice also helps in this case. For example, artificial mold cooling techniques may be used locally to remove the heat rapidly. However, as the castings become larger these problems are magnified.(68) It is evident that research is needed to develop suitable casting methods for large superalloy parts.(87)

Experiments with MAR-M 211 using a grain-refining additive and a constant amount of superheat (150 degrees F) showed that grain size and shape, and casting properties were very dependent on mold preheat temperatures. For example, the following results were obtained, as shown in figure 52.

In this method, the melt temperature is lowered to obtain incipient nucleation as observed on the melt surface, and the power on the crucible increased sharply to the pouring temperature, as shown in figure 53. The sufficient number of nuclei that persist are mixed in the melt by the normal stirring action of the induction coil. The result is a fine equiaxed structure.(94)

Remarkable success has been achieved in developing turbine-blade castings with long columnar grains oriented parallel with the blade axis.(63,92) A refinement of work first published in 1960(79), the process has shown that certain beneficial effects on mechanical properties can be obtained on MAR-M 200(63,92) and on NASA TAZ-8B.(95) Directional grains are obtained by chilling the bottom of the mold and controlling the heat extraction from the rest of the mold as illustrated in figure 54.(95) A smooth temperature gradient is maintained in the vertical direction. With a pouring temperature of 2900 ± 50 F for TAZ-8B, the temperature of the mold next to the chill block was made approximately equal to the melting temperature, 2450 F, while the temperature at the top of the mold was 2750 F. After pouring, the power was gradually reduced, starting with the bottom coil and moving upward.(95)

A recent patent on directional solidification calls for heating the mold by several separately controlled induction coils surrounding a graphite susceptor.(96) Power to the coil is adjusted to maintain a temperature gradient from the top to the bottom of the mold. Additionally, the entire mold assembly can be slowly withdrawn from the induction coil. Figure 55 shows the method as depicted in the patent.

Similar procedures were used for MAR-M 200.(92) The melt temperature was 2850 F, which is 350 degrees F of superheat. Control over the solidification temperature was maintained by monitoring the mold temperature just above the advancing solidification front, which is indicated by a thermal arrest.

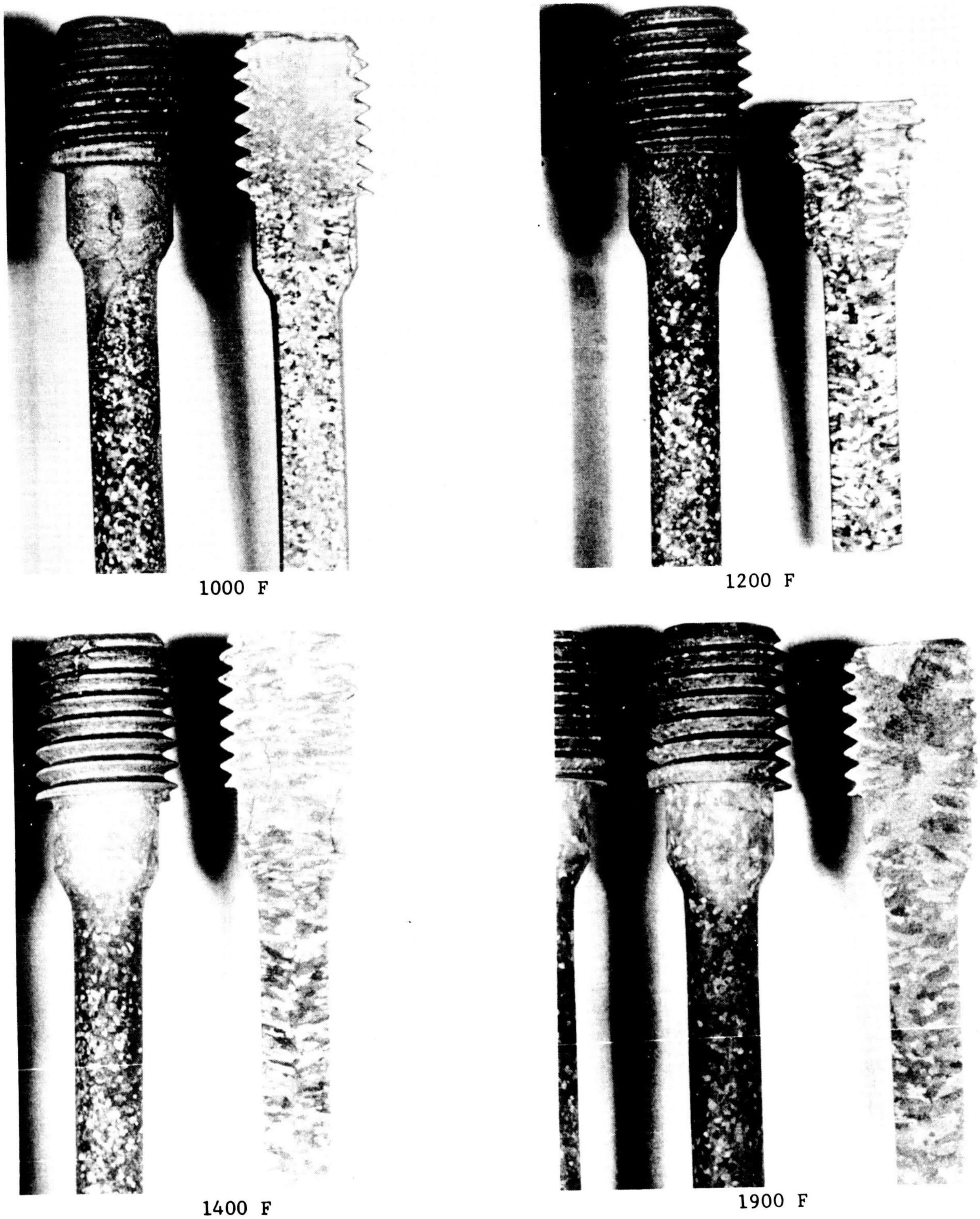


FIGURE 52. GRAIN STRUCTURE OF MAR-M211 POURED AT 150 F SUPER-HEAT, WITH A GRAIN REFINING ADDITIVE IN THE FACE-COAT, AT VARIOUS MOLD PREHEAT TEMPERATURES

(Courtesy Martin Metals Company)

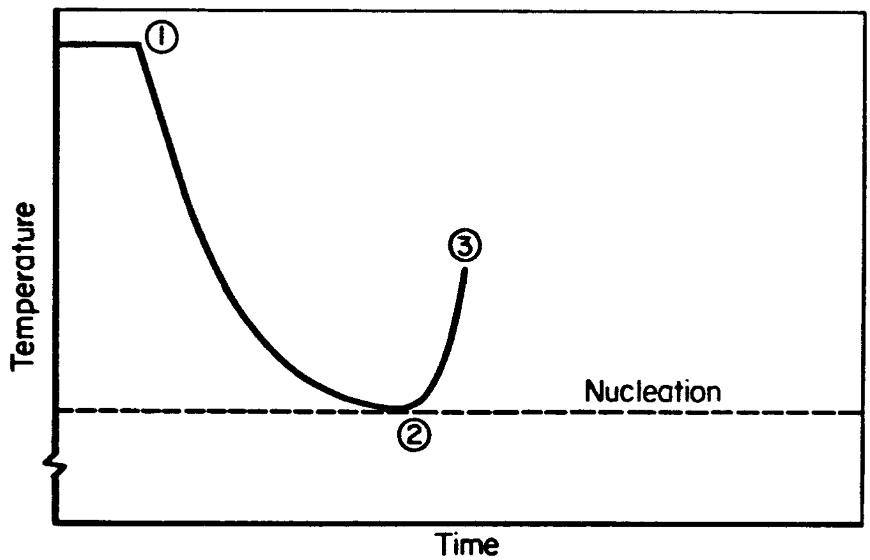


FIGURE 53. TIME - TEMPERATURE CURVE FOR CONTROLLED GRAIN CASTING[94]

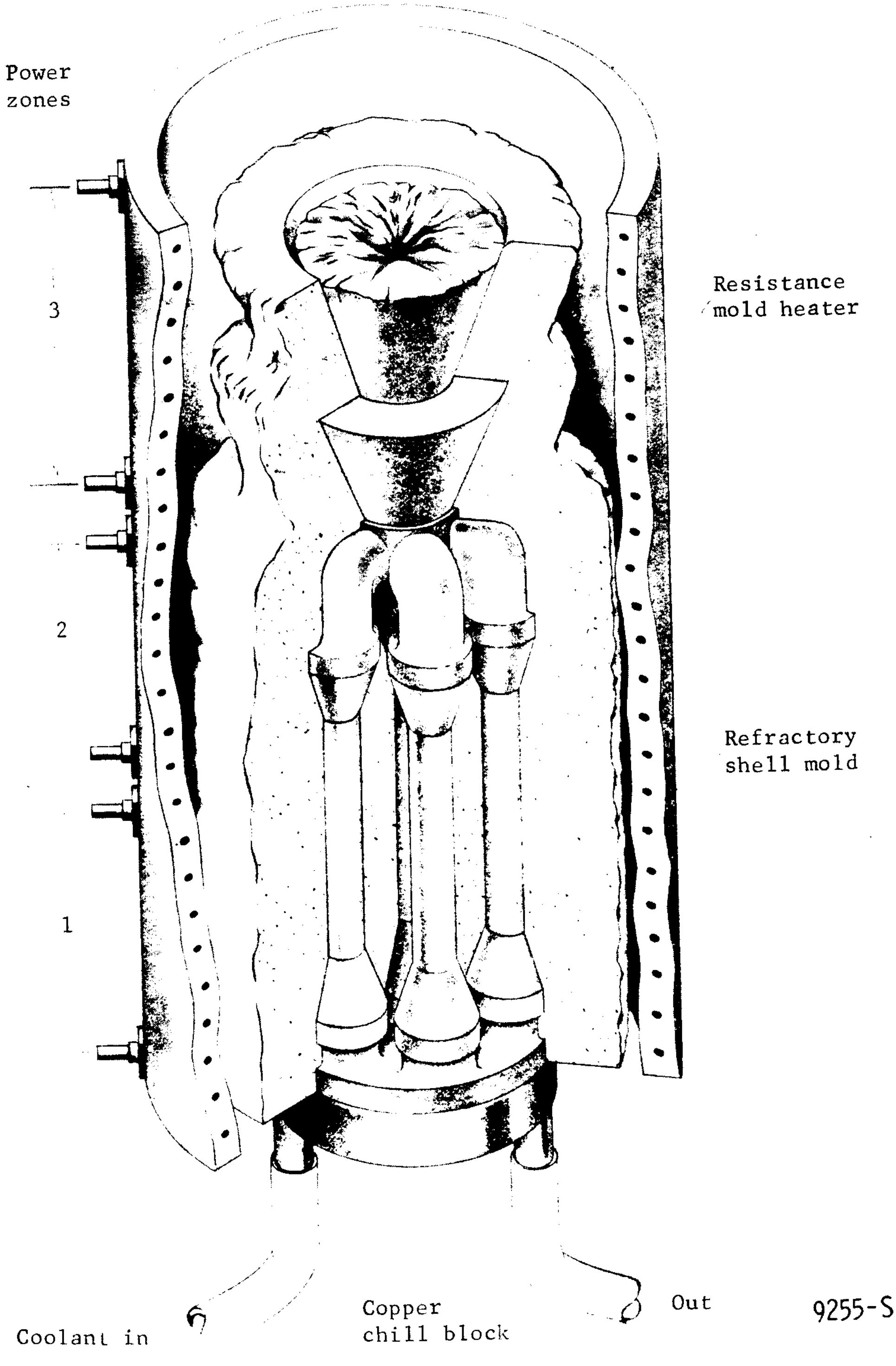


FIGURE 54. CONTROLLED-SOLIDIFICATION CASTING ASSEMBLY[95]

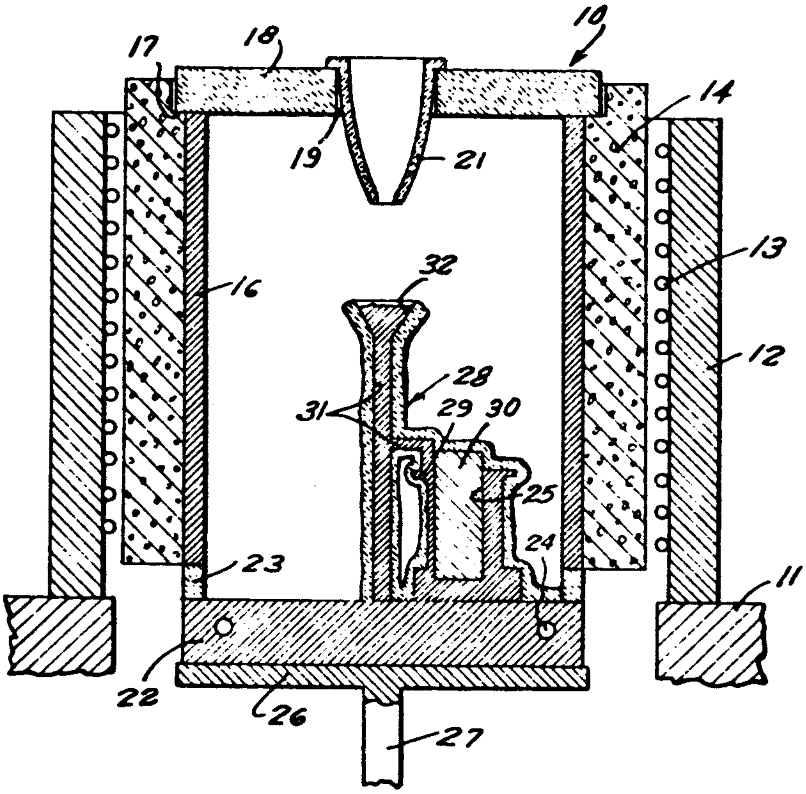


FIGURE 55. METHOD OF DIRECTIONAL SOLIDIFICATION[96]

In operation, the ceramic mold 28 is fastened to the chill plate 22 by means of bolts or clamps. The mold assembly is heated in a gradient fashion by the split induction coil 13 operating through the graphite susceptor 16. The upper portion of the mold would typically be at a temperature above the melting point of the alloy, while the bottom would be held at a temperature below the melting point. After the metal has been poured, the solidification is controlled by adjusting the power to the coils, or in combination with lowering of the mold from the position shown.

Casting of single-crystal blades is similar to that for directionally solidified blades, except that a multiple-turn constriction in the path of the growing columnar grains selects one grain with a [001] orientation for growth. Figures 56 and 57 illustrate the method.(97)

Sizes and Tolerances

A continuous effort is being made to increase the size and dimensional accuracy of vacuum-cast superalloys. On a production basis, 26-inch-diameter castings requiring a 250-pound melt are being made, and 30-inch-diameter castings requiring 550 pounds of alloy can be made on special programs. Examples of relatively large nozzles with hollow vanes are shown in figure 58. Production facilities of one major vacuum caster allow 72-inch-diameter castings and 1000-pound melts(98); another reports a potential of 60-inch castings requiring 3000 pounds of superalloy.(90) Research programs underway are aimed at improving the methods of producing 100-pound structural castings to serve as turbine disks or aircraft fin beams(61), and thin-walled (0.040 to 0.060 inch) castings 48 inches in diameter for a gas-turbine diffuser case.(87)

The recent history of precision vacuum casting has been strongly connected to gas-turbine engine blades, vanes, and integral wheels/blades. Typically, dimensional tolerances run ± 0.005 in./in. of the blueprint specification, although for a given set of tools a smaller variation can be expected from part to part.(67) A typical uncomplicated turbine blade with a 5-inch-long by 2-inch-wide airfoil may be quoted with 0.002 in./in. tolerances(78), but the usual recommended tolerances might be:

±0.003 inch for dimension up to 0.25 inch
±0.004 inch for dimensions from 0.25 to 0.50 inch
±0.005 inch for dimensions from 0.50 to 1.5 inches
±0.005 in./in. for each linear inch over 1 inch.

Closer tolerances than 0.005 in./in. are sometimes called for because in a large casting the accumulated variations in dimension might be unacceptable (more precision than needed should not be specified). Figure 59 shows some nozzle and wheel/blade castings. Tolerances for axial-flow nozzles, radial-flow nozzles, and axial-flow wheel/blades are shown in figure 60.(68) Note that the diameter tolerance on 6 to 7 inch wheels is ±0.022, or about 0.003 in./in.

The basic cause of variations in investment casting is shrinkage. Shrinkage of the pattern, mold, and solidifying metal can be calculated, but deviation of the amount of shrinkage from the expected value causes dimensional variations. It has been found that mold and metal temperature are considerably less important in this respect than in the section thickness and that the ability to control dimensions was directly proportional to the square root of the dimension.(99)

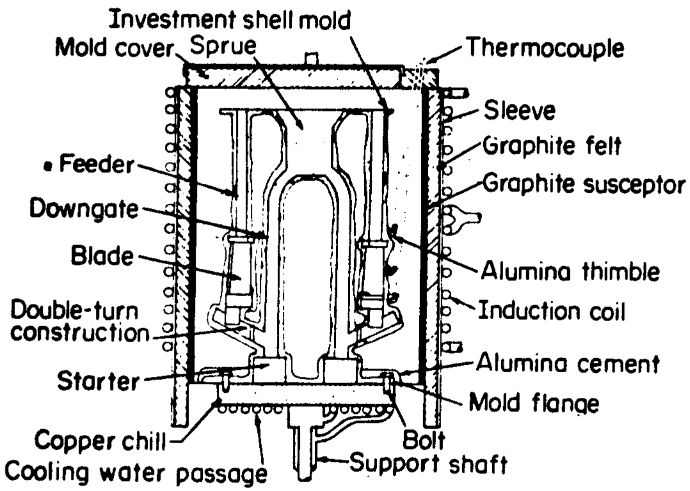


FIGURE 56. MOLD ASSEMBLY FOR PRODUCING SINGLE-CRYSTAL TURBINE BLADES(97)

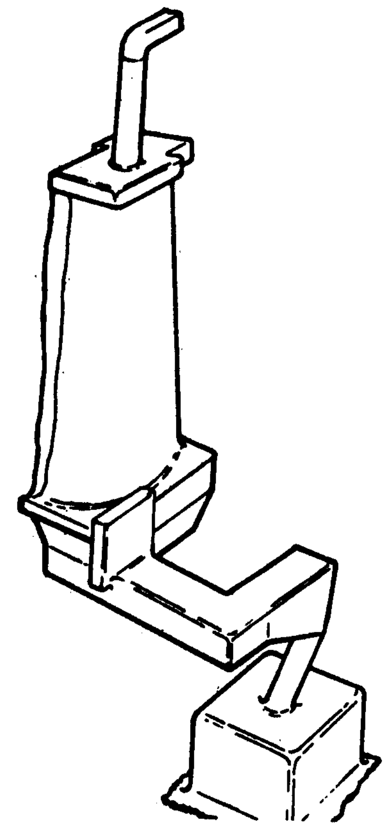


FIGURE 57. CONSTRICTION MOLD FOR PRODUCING CAST SINGLE-CRYSTAL GAS TURBINE BLADES(97)

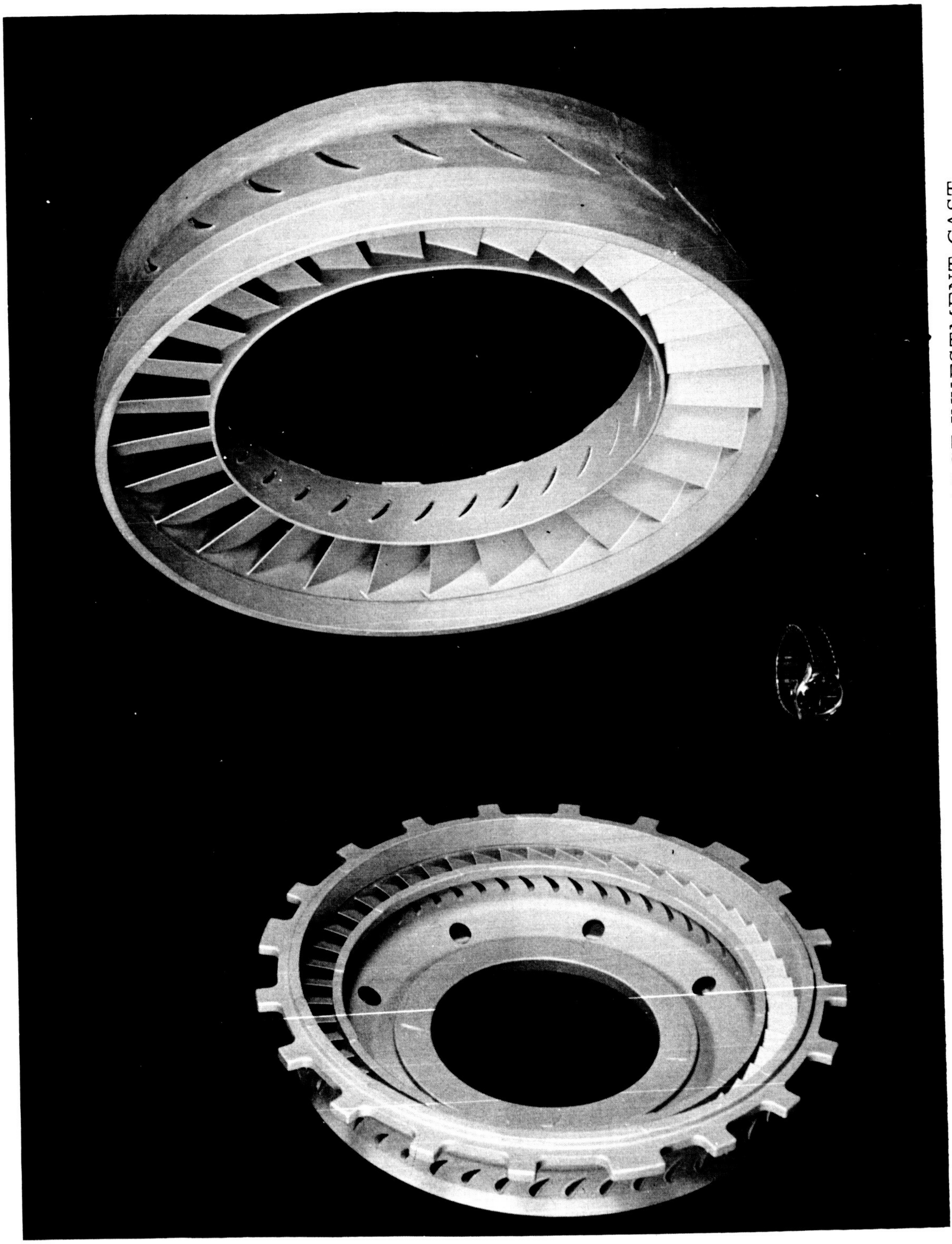


FIGURE 58. EXAMPLES OF RELATIVELY LARGE INVESTMENT CAST TURBINE-ENGINE NOZZLES WITH HOLLOW VANE

(Courtesy Misco Division, Kormet Corporation)

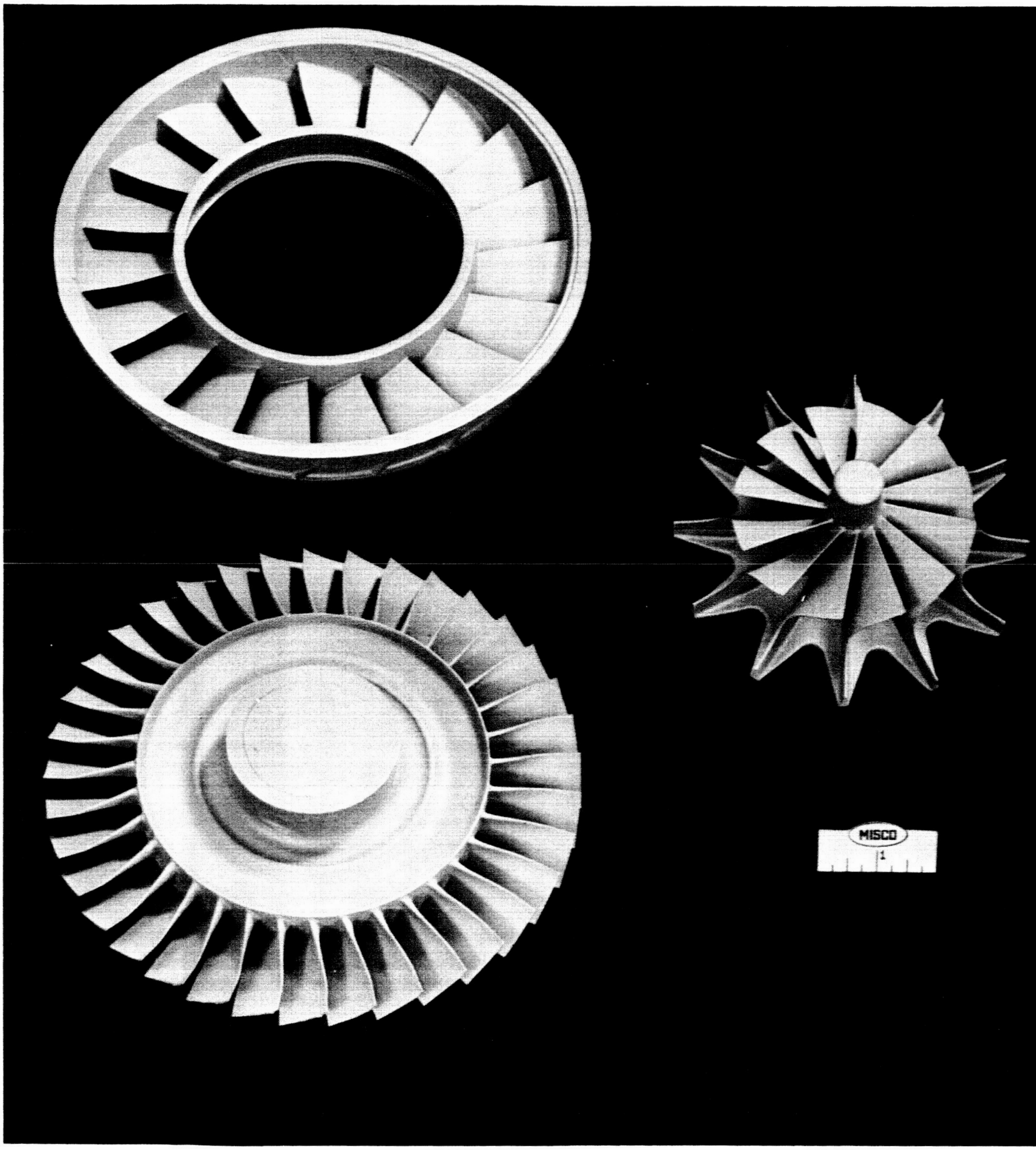
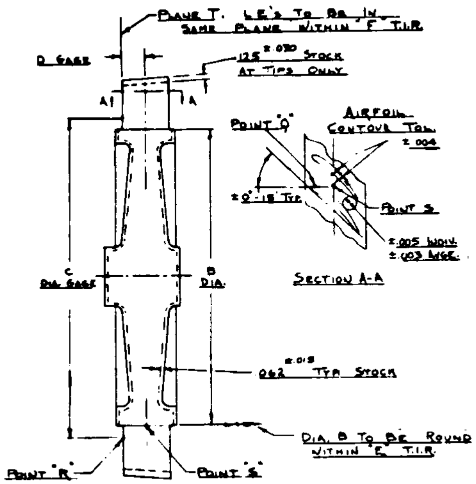
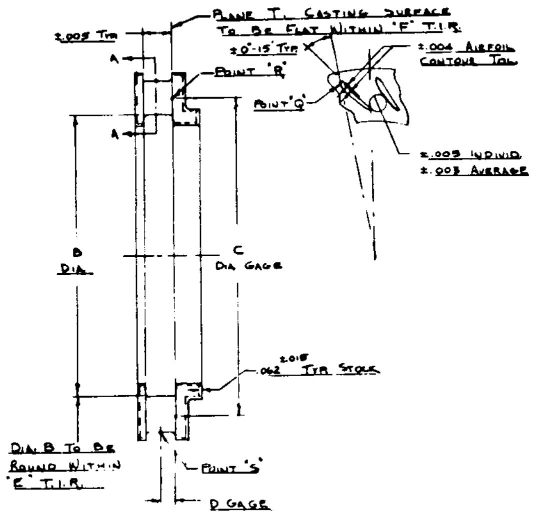


FIGURE 59. CASTINGS OF AXIAL-FLOW NOZZLE (TOP), AXIAL-FLOW WHEEL/BLADES (BOTTOM) AND RADIAL-FLOW WHEELS

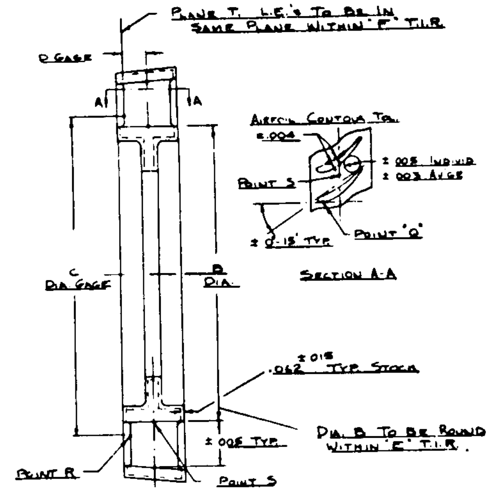
(Courtesy Misco Division, Howmet Corporation)



Axial-Flow Nozzle



Radial-Flow Nozzle



Axial-Flow Integral Wheel / Blades

Notes:

1. For inspection, casting to be located at a diameter defined by average of points 'S', and at a plane defined by average of points 'R'.
2. Blades to be equally spaced within .010 of true position when checked at points 'Q'.
3. Minimum recommended T.E. thickness .025
4. Where special configurations or tolerances are required, consult Misco representative.
5. See table for roundness & flatness.

Dia B ins.	Tol. Dia B	'E' T.I.R.	'F' T.I.R.
3	±.012	.008	.010
4	±.015	.010	.012
5	±.018	.012	.016
6	±.020	.014	.020
7	±.022	.016	.024

FIGURE 60. RECOMMENDED TOLERANCES FOR VARIOUS GAS-TURBINE COMPONENTS(68)

Outlook

Remarkable progress has been made in precision casting of superalloys in the past 10 years – so much so that cast turbine buckets, which rotate at high temperatures and stresses, have won wide acceptance. No longer is there a reluctance to choose cast alloys over forged alloys, because good production and inspection techniques, together with actual operating experience, have shown that the castings are reliable.

What can be expected for the future? Research on vacuum casting is proceeding in three directions: toward better alloys and metallurgical control, toward increased equipment capabilities (that is, toward larger castings), and toward increased capabilities for making complex parts.[70,98]

In the metallurgical area, we have seen new alloys being introduced steadily in the past 5 years, some developed by private industry and some by government. This trend can be expected to continue in order to satisfy the demand for stronger, more corrosion-resistant alloys with longer service lifetimes. Sometimes the approach has been not toward new alloys but toward controlled grain structures as exemplified by directionally solidified or even single-crystal turbine blades. This trend can also be expected to continue, although economics and technical requirements may be joined in battle. A typical directionally cooled airfoil requires up to 6 hours to complete, obviously a very costly operation. Moreover, the longer time in contact with the mold refractory is detrimental and will require new refractories and possibly new alloys especially designed for this technique.

More research is being directed towards greater complexity of castings, especially those with delicately cored passages. Close cooperation of ceramists, metallurgists, and other technologists is required. In general, increased shape capabilities with increased precision are being sought. One problem to overcome is the loss of ductility in thin sections and in very thick sections. Furthermore, research is now underway to relate foundry variables to the observed low creep-rupture life in thin cast sections. Among the variables studied are mold preheating temperature, superheat at the time of pouring, and cooling rate after the mold is filled. Good correlation was found between the creep-rupture life and the amount of micro-shrinkage. More investigations of this type can be expected as the needs for better quality control in complex castings are increased.

Larger vacuum castings can be expected, but the increased size will be accompanied by a strong effort toward solving the problems of dimensional accuracy, without which casting might lose its advantage over the other methods. Control of microstructure, particularly microsegregation, in large castings presently limits turbine-wheel castings to 24 inches in diameter, and this problem will engage metallurgist and precision-casting technologists, especially in the gas-turbine industry.[70] An example of a large structural component is shown in figure 61.

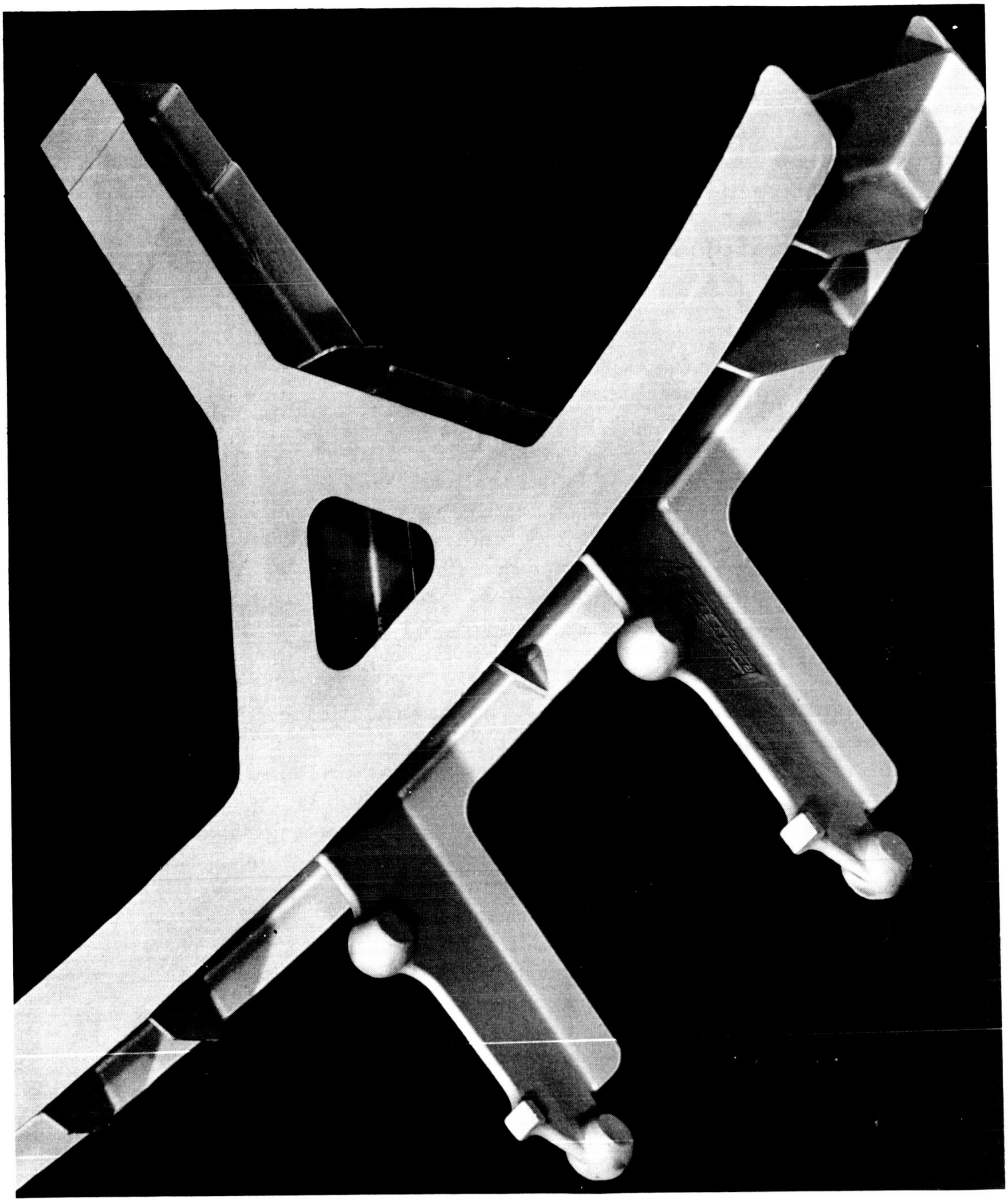


FIGURE 61. EXAMPLE OF A LARGE PRECISION-CAST STRUCTURAL COMPONENT

(Courtesy Austenal Microcast Division, Howmet Corporation)

The next 10 years, just as the past 10, seem likely to see wide expansion of the scope of vacuum-cast superalloys, especially in the field of air- and ground-transportation systems.

APPENDIX

COMPILATION OF FACILITIES AVAILABLE IN THE U. S.

The tables presented herein list and describe the vacuum-induction melting, vacuum-arc remelting, and electroslag-remelting facilities of those companies known to be producing superalloy ingots. These data were derived primarily from the literature sources noted at the end of each table and were updated to the extent that additional information was available.

TABLE A-1. VACUUM-INDUCTION-FURNACE

(50 Pounds

Company and Plant Location	Furnaces	Equipment Suppliers Melting	Equipment Suppliers Vacuum	Furnace Capacity, lb	Power Supply, kw rating
Allvac, a Teledyne Company Monroe, N. C.	1	Inductotherm	Stokes	3,000	375
	1	Inductotherm	Stokes	17,000	1,200
	1	CVC	CVC/Kinney	50	30
Armco Steel Corporation Baltimore, Md.	1	Inductotherm	Stokes/Elliott	50,000	2,500
Arwood Corporation Groton, Conn.	1	Inductotherm	Heraeus-Engelhard	50	150
Bethlehem Steel Corporation Bethlehem, Pa.	1	CVC	CVC/Kinney	500	175
Cameron Iron Works Houston, Texas	1	Inductotherm	Elliott	20,000	2,500
	1	Inductotherm Cameron	Elliott	60,000	2,500
Cannon-Muskegon Corporation Muskegon, Mich.	1	Tocco	Stokes	60	100
	1	Tocco	Stokes	400	100

INSTALLATIONS IN THE U. S.[a]

and Over)

Power Supply, Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single Ingot Mold or Multiple Casts	Alloying Methods	Product	Materials Melted[b]
960	3,000	1,000	Manual, vacuum locks	Multiple casts	Through vacuum locks	Ingots, electrodes, remelt stock	HTA, NBA, CBA, SA
180	15,000	3,600	Manual overhead, vacuum locks	Multiple casts	Through vacuum locks	Electrodes, ingots	HTA, NBA, CBA, SA
4,200	30	30	Through vacuum locks	Both	Through vacuum locks	Ingots, electrodes	Experimental alloys
60	47,000	NA	Hot metal through vacuum lock, top load cold charge	Multiple casts	Through vacuum locks	Ingots, electrodes	S, SA, HTA, SS
3,000	30	200	Slug	Single-ingot mold	Rotating cups	Castings	HTA
960	300	150	Manual	Both	Multiple buckets, vacuum locks	Ingots, castings	BS, HPA, HTA, IBA, LA, LC, MC, NBA, S, SS, SA, SP-A, TS
180	20,000	8,000		Multiple casts	Through vacuum locks		NBA, BS, CBA, HTA, IBA, S, SA
180	50,000	10,000		Multiple casts	Through vacuum locks		NBA
3,000	60	60	Manual overhead, vacuum locks	Both	Vib hoppers	Castings, ingots	LA, S, NBA, CBA, HTA, SA, SP-A, IBA, SS
3,000	400	200	Manual overhead, vacuum locks	Both	Vib hoppers	Ingots, remelt stock	LA, S, NBA, CBA, HTA, SA, SP-A, IBA, SS

TABLE A-1.

Company and Plant Location	Furnaces	Equipment Suppliers: Melting	Equipment Suppliers: Vacuum	Furnace Capacity, lb	Power Supply, kw rating
Cannon-Muskegon Corporation Muskegon, Mich.	1	Inductotherm	Stokes	1,200	350
	1	Inductotherm	Stokes	2,400	350
	1	Inductotherm	Stokes	3,200	350
Carpenter Steel Company Reading, Pa.	1	Ajax	Stokes/Ajax	15,000	1,500
	1	Ajax	Stokes	1,500	300
Crucible Steel Company of America Syracuse Works Syracuse, N. Y.	1	NRC	Kinney/NRC	3,000	700
	1	NRC	Kinney/NRC	3,000	600
	1	NRC	Kinney/NRC	3,000	700
Cyclops Corporation Universal-Cyclops Specialty Steel Division Pittsburgh, Pa.	1	Stokes	CVC	2,000	350
	1	NCR	CVC	3,500	500
	1	CVC	CVC	50	100

(Continued)

Power Supply, Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single-Ingot Mold or Multiple Casts	Alloying Methods	Product	Materials Melted[b]
1,000	1,200	550	Manual overhead, vacuum locks	Both	Vib hoppers and top leader	Ingots, remelt stock	LA, S, NBA, CBA, HTA, SA, SP-A, IBA, SS
1,000	2,400	550	Manual overhead, vacuum locks	Both	Vib hoppers, top loader	Ingots, remelt stock	LA, S, NBA, CBA, HTA, SA, SP-A, IBA, SS
1,000	3,200	1,000					
180	15,000		Manual overhead bulk and controlled rate through vacuum locks	Both	Through vacuum locks	Ingots, electrodes	HTA, S, NBA, TS, EA, IBA, SS, SA, SPA
960	1,500	NA	Manual overhead	Both	Through vacuum locks	Ingots, electrodes	HTA, S, NBA, TS, EA, IBA, SS, SA, SPA
960	2,800	525		Both	Through air locks		S, SA, TS, BS, pure iron
960	2,800	525		Both			S, SA, TS, BS, pure iron (both rows)
960	2,800	525		Both	Through air locks		
960	2,000		Overhead	Both	Through vacuum locks		BS, EA, HTA, NBA, S, SS, SA, SP-A
960	3,500		Overhead	Both	Through vacuum locks		BS, EA, HTA, NBA, S, SS, SA, SP-A
3,000	50						BS, EA, HTA, NBA, S, SS, SA, SP-A

TABLE A-1.

Company and Plant Location	Furnaces	Equipment Suppliers Melting	Equipment Suppliers Vacuum	Furnace Capacity, lb	Power Supply, kw rating
Wilbur B. Driver Company Newark, New Jersey	1	Tocco	Stokes	2,000	350
	1	Inductotherm	Stokes	5,000	1,000
	1	Geraetebau-Anstalt	Bendix Balzer	70	100kw
Driver-Harris Company Harrison, N. J.	1	CVC	CVC	600	176
Eastern Stainless Steel Corporation Baltimore, Md.	1	Inductotherm	Stokes	3,500	350
	1	Geraetebau-Anstalt	Bendix Balzer	70	100
Firth-Sterling, Inc. McKeesport, Pa.	1	Ajax	Elliott	5,000	300
General Electric Company Schenectady, N. Y.	1	Ajax	Ajax/Elliott	50,000	3,000
Philadelphia, Pa.	1	Inductotherm	Stokes	50	50
Howmet Corporation Austenal Microcast Division Dover, N. J.	1	Inductotherm	NRC	3,000	350
	1	Inductotherm	Hull	4,000	700
	1	Ajax	Heraeus-Engelhard	12,000	1,000
	1	NRC	NRC	200	100

(Continued)

Power Supply, Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single-Ingot Mold or Multiple Casts	Alloying Methods	Product	Materials Melted(b)
960	2,000	900	Vacuum lock	Both	Vib hopper	Ingots	EA, HPA, NBA, SP-A, HTA
180	5,000	2,000	Vacuum lock	Both	Vib hopper	Ingots	EA, HPA, NBA, SP-A, HTA
2,500	70		Top loaders	Tundish and direct, single ingot	Vacuum lock chute	Ingots	HTA, NBA
960	600	600	Manual through vacuum locks	Both	Vib hopper	Ingots	EA, HTA, NBA, S, SP-A
960	3,500	1,000	Manual overhead	Both	Through vacuum locks	Ingots, remelt stock	S, CBA, HTA, NBA, SS, SA, Sp-A
2,500	70	NA	Top loaders	Single-ingot mold			HTA, NBA
180	5,000	1,000	Through vacuum locks	Both	Vacuum lock canisters	Ingots, electrodes	HTA, CBA, IBA, NBA
180	50,000	15,000		Both	Multiple buckets		
3,000	50						
960	3,400	1,000	Chute	Multiple casts	Chute	Remelt stock	HTA
960	4,400	2,000	Conveyor	Multiple casts	Conveyor	Remelt stock, ingots	HTA
180	5,000	2,500	Conveyor	Multiple casts	Conveyor	Electrodes, remelt stock, ingots	HTA
3,000	60	NA	Slug	Single-ingot mold		Castings	HTA

TABLE A-1.

Company and Plant Location	Furnaces	Equipment Suppliers Melting	Equipment Suppliers Vacuum	Furnace Capacity, lb	Power Supply, kw rating
Howmet Corporation Austenal Microcast Division Dover, N. J.	1	Inductotherm	Heraeus-Englehard	50	150
	1	Inductotherm	Stokes	100	100
	1	Inductotherm	Heraeus-Englehard	50	150
Misco Division Muskegon, Mich.	1	Ajax	Stokes	100	100
International Nickel Company, Inc. Huntington Alloy Products Division Burnaugh, Ky.	1	Ajax	Elliott	5,000	1,000
Kelsey Hayes Company Philadelphia, Pa.	1	Inductotherm	Stokes	100	100
Latrobe Steel Company Latrobe, Pa.	1	Stokes	Stokes	2,000	333
	1	Inductotherm	Stokes/Elliott	60,000	2,400
Martin Metals Wheeling, Ill.	1	Inductotherm	CVC/Kinney	500	175
	1	Inductotherm	Stokes/CVC	5,000	700
	3	Inductotherm	Stokes	50	50
Pratt and Whitney Company Manchester, Conn.	1(c)	Ajax	CVC	50	100
	1(c)	Inductotherm	Vacuum Industries	50	30

(Continued)

Power Supply, Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single-Ingot Mold or Multiple Casts	Alloying Methods	Product	Materials Melted(b)
3,000	30	NA	Slug	Single-ingot mold		Castings	HTA
3,000	45	NA	Slug	Single-ingot mold		Castings	HTA
3,000	30	NA	Slug	Single-ingot mold		Castings	HTA
3,000	50	200	Top loader	Single-ingot mold	Through vacuum locks	Castings	NBA
180	5,000	2,000	Vacuum lock canisters	Multiple casts	Vacuum lock canisters	Ingots, electrodes	NBA
3,000	100	200					
960	2,000		Cold charge	Multiple ingots and casts	Through vacuum locks	Ingots, electrodes	HTA, BNA, SS
60	15,000-60,000		Hot metal through vacuum lock or cold charge	Multiple ingots and casts	Through vacuum locks	Ingots, electrodes	HTA, NBA, SS
960	650	650	Manual through vacuum locks	Multiple casts	Through vacuum locks	Remelt, ingots, castings	HTA
960	5,000	2,000	Manual through charging locks	Multiple casts	Through vacuum locks	Remelt, ingots	HTA
960	20	100	Through vacuum lock	Both		Castings	HTA
3,000	15	200	Vacuum locks	Single mold	None	Castings	NBA, CBA, HTA
3,000	20	NA	Manual vacuum locks	Single mold	Vacuum locks	Castings, ingots	Experimental alloys

TABLE A-1.

Company and Plant Location	Furnaces	Equipment Suppliers		Furnace Capacity, lb	Power Supply, kw rating
		Melting	Vacuum		
Sherwood Metals Division H. J. Sherwood, Inc. Cleveland, Ohio	2	Stokes	Stokes	50	50
Special Metals Corporation New Hartford, N. Y.	1	Ajax	CVC	100	100
	2	Tocco	Stokes	1,200	300
	1	ASEA	Stokes	2,200	550
	1	ASEA	Stokes	5,000	1,100
	1	Inductotherm	Stokes	12,000	1,200
	1	Ajax	Elliott	30,000	3,300
TRW Metals Division, TRW, Inc. Minerva, Ohio	1	Inductotherm	CVC	10,000	1,200
	4	Inductotherm	Stokes	50	50
	1	Inductotherm	NRC	50	50
	1	Inductotherm	NRC	3,000	500
Union Carbide Corporation Stellite Division	1	Inductotherm	Stokes	10,000	1,700
	1	Inductotherm	NRC	150	150
Western Electric Company Chicago, Ill.	2	Inductotherm	Stokes	600	250
Wyman-Gordon Company Worcester, Mass.	1	Inductotherm	Bendix Balzer	2,500	500

(Continued)

Power Supply, Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single-Ingot Mold or Multiple Casts	Alloying Methods	Product	Materials Melted(b)
4,000	50	150	Single chamber side loader	Single-ingot mold	None	Castings	CBA, NBA
10,000	100	100	Manual	Both	Rotating cups, vacuum locks	Ingots	NBA, SS
3,000	1,200	400	Manual	Both	Rotating cups, vacuum locks	Ingots	NBA, SS
890	2,200	1,200	Manual	Both	Rotating cups, vacuum locks	Ingots, remelt stock	NBA, SS
890	5,000	2,500	Manual	Both	Rotating cups, vacuum lock	Ingots, remelt stock	NBA, SS
180	12,000	5,000	Manual	Both	Rotating cups, vacuum locks	Ingots	NBA, SS
180	30,000	15,000	Manual	Both	Through vacuum locks	Ingots	NBA, SS
180	10,000	1,000	Manual	Both	Vacuum lock	Ingots, remelt stock	NBA, SS
3,000	50	150	Manual	Both	Manual	Castings	NBA, SS
3,000	50	150	Manual	Both	Manual	Castings	NBA, SS
960	3,000	1,500	Manual	Both	Vacuum lock	Ingots, remelt stock	NBA, SS
180	10,000	5,000		Both		Remelt stock	HTA, SA, NBA, CBA, IBA
	100			Multiple molds		Remelt stock	SA
960	600	750	Overhead vacuum lock	Both	Through vacuum locks	Ingots	NBA
960	2,500	500	Overhead vacuum locks	Both	Through vacuum locks		HTA, SA, SS

TABLE A-1.

Company and Plant Location	Furnaces	Equipment Suppliers		Furnace Capacity, lb	Power Supply, kw rating
		Melting	Vacuum		
Wyman-Gordon Company Worcester, Mass.	1	Stokes	Stokes	150	50
	1	Bendix Balzer	CVC/Kinney	20,000	1,500

(a) Material in this table was taken from 33 Magazine, June, 1967.

(b) HTA – high-temperature alloys
NBA – nickel-base alloys
CBA – cobalt-base alloys
IBA – iron-base alloys
SA – superalloys
S – steel
SS — stainless steel
SP-A — specialty alloys

(c) Research only.

(Continued)

Power Supply Output Frequency, cps	Avg Heat Size, lb	Melting Rate, lb/hr	Charging Method	Pouring Method, Single-Ingot Mold or Multiple Casts	Alloying Methods	Products	Materials Melted[b]
3,000	100	50	Overhead vacuum locks	Both	Through vacuum locks		HTA, SA, SS
180	10,000	1,500	Overhead vacuum locks	Both	Through vacuum locks		HTA, SA, SS

TABLE A-2. CONSUMABLE-ELECTRODE VACUUM-ARC-FURNACE INSTALLATIONS IN THE U. S.[a]

Company and Location	Furnaces	Furnace Manufacturer	Lb/Year[b] Capacity	Max. Ingot Dia, in.	Max. Ingot Wt, lb	Amperes	Materials Melted
Allegheny Ludlum Steel Corporation Watervliet, N. Y.	6	Own design	23,200,000	28	20,000	NA	Low alloy, electrical and magnetic, tool and die, stainless, superalloys, bearing steels
	1	Lectromelt	9,000,000	50	50,000	NA	Low alloy, electrical and magnetic, tool and die, stainless, superalloys
	2	Heraeus					
Allvac Metals Company Monroe, N. C.	1	Zak	1,500,000	12	3,500	7,500	Nickel-, iron-, and cobalt-base alloys
	3	Consarc	2,700,000	24	10,000	12,500	Nickel-, iron-, and cobalt-base alloys
Armco Steel Corporation Baltimore, Maryland	1	Consarc		40	40,000	35,000	Stainless, nickel-base, and high-temperature alloys
	1	Consarc	8,000,000	36	35,200	35,000	
Braeburn Alloy Steel Division Cont'l Cooper and Steel Ind., Inc. Braeburn, Pa.	1	Lectromelt	3,500,000	30	20,000	17,500	High-temperature, high-strength bearing steels and special-applications steels, superalloys
	1	Heraeus	NA	6	150	1,800	
Cameron Iron Works, Incorporated Houston, Texas	20	Own design	70,000,000	50	70,000	NA	High-strength steels, superalloys
Carpenter Steel Company Reading, Pennsylvania	6	Heraeus	9,000,000	20	12,000	NA	Stainless high-temperature alloys, electronic alloys, tool steels and special alloys, superalloys
	2	N. R. C.	9,000,000	20	6,000,000	NA	
	2	Lectromelt	12,000,000	28	28,000	NA	
Crucible Steel Company of America Syracuse, N. Y.	1	Heraeus		36			Low-alloy, tool and die, superalloys, high-temperature alloys
	1	Lectromelt	8,000,000	30	26,000	NA	
	1	Consarc	6,000,000	30	25,000	NA	
Eastern Stainless Steel Corporation Baltimore, Maryland	1	Heraeus	2,000,000	20	10,000	10,000	Nickel-, cobalt-, and iron-base superalloys and stainless steels
Huntington Alloy Products Division, The International Nickel Company, Inc. Huntington, W. Va.	1	Lectromelt[c]	3,500,000	30	24,000	25,000	High nickel-base alloys

TABLE A-2. (Continued)

Company and Location	Furnaces	Furnace Manufacturer	Lb/Year(b) Capacity	Max. Ingot Dia. in.	Max. Ingot Wt, lb	Amperes	Materials Melted
Latrobe Steel Company Latrobe, Pa.	2	Consarc		24	15,000	15,000	
	2	Lectromelt	12,000,000	20	8,000	NA	Alloys, high-temperature alloys, superalloys
	1	Lectromelt	8,000,000	30	28,000	NA	Alloys, high-temperature alloys, superalloys
	1	Lectromelt	8,000,000	36	30,000	NA	Alloys, high-temperature alloys, superalloys
	1	Heraeus		40	60,000		
Midvale-Heppenstall Company Philadelphia, Pa.	2	Allegheny		21	9,300	NA	Low-alloy, stainless, superalloys
		Ludlum	12,000,000				
	1	Heraeus		60	100,000	NA	Low-alloy, stainless, superalloys
National Lead Company Nuclear Metals Division Albany, N. Y.	2	Lectromelt	100,000	10	750	NA	Zirconium, superalloys, uranium, titanium alloys, thorium
Nuclear Metals, Division of Textron, Inc. West Concord, Mass.	1	Own design	500,000	8	500	6,000	Uranium, zirconium, titanium, and their alloys, special steels, nickel- and iron-base alloys
	1	Own design	37,500	3	25	NA	
Republic Steel Corporation Canton, Ohio	4	Consarc		40	40,000	30,000	
	4	Own design	25,000,000	32	30,000	NA	High-temperature stainless alloys, superalloys
Special Metals Corporation New Hartford, N. Y.	2	Consarc		24	15,000	12,500	
	2	Heraeus(c)	6,000,000	20	22,000	14,000	Nickel-base, high-temperature alloys, specialty steels
Standard Steel Works Division, Baldwin-Lima-Hamilton Corporation Burnham, Pa.	1	Lectromelt(c)	8,000,000	40	50,000	35,000	Stainless, nickel-, and iron-base alloys
	1	Lectromelt	8,000,000	30	22,000	25,000	Stainless, nickel-, and iron-base alloys
Timken Roller Bearing Canton, Ohio	1	Westinghouse	5,400,000	24	10,000	NA	Low-alloy electrical and magnetic, stainless, superalloys, tool and die
	1	Consarc		40	40,000	30,000	

TABLE A-2. (Continued)

Company and Location	Furnaces	Furnace Manufacturer	Lb/Year[b] Capacity	Max. Ingot Dia, in.	Max. Ingot Wt, lb	Amperes	Materials Melted
Union Carbide Corporation Stellite Division Kokomo, Indiana	1	Consarc	1,200,000	30	35,000	17,500	Special-alloy, nickel-, cobalt-, columbium-, and some iron-base
	1	Consarc	1,200,000	30	35,000	25,000	
Universal-Cyclops Specialty Steel Division, Cyclops Corporation Bridgeville, Pa.	2	Own design	12,000,000	25	14,000	NA	Refractory metals, high-temperature, high-strength metals, tool steels, stainless steels, superalloys, magnetic and electronic metals
	2	G. E.	NA	NA	NA	NA	
Titusville, Pa.	2	Lectromelt	20,000,000	40	50,000	NA	
Vasco, A Teledyne Company Latrobe, Pa.	2	Consarc		33	33,000	25,000	Iron- and nickel-base alloys, ultrahigh-strength steels, bearing steels, superalloys
	1	Heraeus	30,800,000	33	25,000	21,000	
	1	Heraeus[c]	(combined)	24	9,000	14,000	
Armetco Division Wooster, Ohio	1	Own design		12	NA	NA	
Westinghouse Electric Corporation Blairsville, Pa.	1	Lectromelt[c]	4,000,000	23	9,500	17,500	Nickel-, cobalt-, molybdenum-, and iron-base alloys
Wyman-Gordon Company Worcester, Mass.	1	Heraeus	1,500,000	16	6,000	10,000	High-temperature and superalloys
	2	Heraeus	4,000,000	20	10,000	10,000	High-temperature and superalloys

(a) Most of the information in this table was taken from 33 Magazine, July (1965), 76-77.
(b) Figures furnished by companies listed are believed to be conservative.
(c) Modernized by Consarc '63 - '65.

TABLE A-3. ELECTROSLAG-REMELTING-FURNACE INSTALLATIONS IN THE U. S.[a,b]

Company and Location	Furnaces	Furnace Manufacturer	Capacity, lb/year	Max. Ingot Dia, in.	Max. Ingot Wt, lb	Amperes	Materials Melted
Cyber Metals, Inc. Philadelphia, Pa.	1	Arcos		4 x 4	Continuous melting		Stainless steel, superalloys
Firth Sterling, Inc. McKeesport, Pa. Hopkins Process-Flux Melting	3	Own design	12,000,000	16	5,000	12,500	High-temperature alloys, stainless, high-speed hot-work die, low-alloy steels
Union Carbide Corporation Materials Systems Division Kokomo, Ind.	1 1	Consarc Consarc	1,200,000 1,200,000	30 30	35,000 35,000	17,500 25,000	Special-alloy, nickel-cobalt-, columbium-, and some iron-base alloys
Union Electric Steel Corporation	1	Firth Sterling/ Heraeus		30			

(a) 33 Magazine, July, 1965, 76-77.
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